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EMERGENCY ASCENT TRAJECTORIES  
FOR DEEP SUBMERSIBLES

by

HERBERT WILLIAM TUFTS, III

June, 1969



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B.S., Virginia Polytechnic Institute

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SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE DEGREE OF  
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AND THE DEGREE OF  
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ABSTRACT

EMERGENCY ASCENT TRAJECTORIES  
FOR DEEP SUBMERSIBLES

by

HERBERT WILLIAM TUFTS, III

Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1969 in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Ocean Engineering.

After a brief discussion of the need for predicting the emergency ascent trajectory of a submersible and the means by which a mathematical model of an ascent can be derived, the second order, coupled equations of motion for a vehicle with varying mass and center of mass are derived.

The equations of motion are then solved by a numerical step-wise procedure which is amenable to programming on a digital computer.

Ascent trajectories are calculated using data from model experiments on the Deep Submergence Rescue Vehicle.

The tests indicate that two dimensional, vertical plane, equations are all that are necessary to determine an ascent through an undisturbed medium, but are insufficient once the vehicle is disturbed from its vertical plane.

Thesis Supervisor: Martin A. Abkowitz

Title: Professor of Naval Architecture



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All computer programs were written for and executed by the IBM 360 Digital Computer of the Information Processing Center of Massachusetts Institute of Technology.



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# NOMENCLATURE

Symbol	Dimensionless Form	Definition
$A_B, A_E$		Body and earth fixed axis systems respectively
$B$	$B' = B/\frac{1}{2}\rho l^2 U^2$	Buoyancy force, positive upward
$CB$		Center of buoyancy of submersible
$CG$		Center of gravity or mass of submersible
$I_G, I_o$		Inertial tensor (3 x 3) about vehicle CG and vehicle origin respectively
$I_{xx}$	$I'_{xx} = I_{xx}/\frac{1}{2}\rho l^5$	Moment of inertia of submersible about x axis
$I_{yy}$	$I'_{yy} = I_{yy}/\frac{1}{2}\rho l^5$	Moment of inertia of submersible about y axis
$I_{zz}$	$I'_{zz} = I_{zz}/\frac{1}{2}\rho l^5$	Moment of inertia of submersible about z axis
$I_{xy}$	$I'_{xy} = I_{xy}/\frac{1}{2}\rho l^5$	Product of inertia of submersible about xy plane





$I_{xz}$	$I'_{xz} = I_{xz} / \frac{1}{2} \rho l^5$	Product of inertia of submersible about xz plane
$I_{yz}$	$I'_{yz} = I_{yz} / \frac{1}{2} \rho l^5$	Product of inertia of submersible about yz plane
K, H, N	$K' = K / \frac{1}{2} \rho l^3 U^2$	Rolling, pitching and yawing moments respectively
$K_u$	$K'_u = K_u / \frac{1}{2} \rho l^3 U = \partial K' / \partial u'$	Typical static moment derivative; derivative of a moment component with respect to a velocity component, $\partial K / \partial u$
$K_{\dot{u}}$	$K'_{\dot{u}} = K_{\dot{u}} / \frac{1}{2} \rho l^4 = \partial K' / \partial \dot{u}'$	Typical moment of inertia coefficient; derivative of a moment component with respect to an acceleration component, $\partial K / \partial \dot{u}$
$K_p$	$K'_p = K_p / \frac{1}{2} \rho l^4 U = \partial K' / \partial p'$	Typical rotary moment derivative with respect to an angular velocity component, $\partial K / \partial p$



$K_p$ 

$$K'_p = K_p / \frac{1}{2} \rho l^5 = \partial K' / \partial \dot{p}$$

Typical moment of inertia coefficient; derivative of a moment component with respect to an angular acceleration component,  $\partial K / \partial \dot{p}$

 $K_{vw}$ 

$$K'_{vw} = K_{vw} / \frac{1}{2} \rho l^3 = \partial^2 K' / \partial v' \partial w'$$

Typical second order moment coefficient; derivative of a moment component with respect to the square of a velocity component or the product of two velocity components,  $\partial^2 K / \partial v \partial w$

 $K_{vq}$ 

$$K'_{vq} = K_{vq} / \frac{1}{2} \rho l^4 = \partial^2 K' / \partial v' \partial q'$$

Typical second order moment coefficient; derivative of a moment component with respect to the product of a velocity component with an angular velocity component,  $\partial^2 K / \partial v \partial q$

 $K_{pq}$ 

$$K'_{pq} = K_{pq} / \frac{1}{2} \rho l^5 = \partial^2 K' / \partial p \partial q$$

Typical second order moment coefficient; derivative of a moment component with respect to the square of an angular velocity component or the product of two angular velocity components,  $\partial^2 K / \partial p \partial q$



$K_*$	$K'_* = K_*/\frac{1}{2}\rho l^3 u^2$	Typical moment coefficient when body angles ( $\alpha, \beta$ ) and control surface angles are zero
$l$	$l' = l/l = 1$	Characteristic length of the submersible
$m$	$m' = m/\frac{1}{2}\rho l^3$	Mass of submersible, including water in ballast tanks
$0$		Origin of body axes
$p, q, r$	$p' = pl/U$	Angular velocities of roll, pitch and yaw, respectively
$\dot{p}, \dot{q}, \dot{r}$	$\dot{p}' = \dot{p}l^2/U^2$	Angular accelerations of roll, pitch, and yaw, respectively
$t$	$t' = t U/l$	Time
$T_A, T_B$		Angular and translational velocity transformation matrices, respectively; transformation is from body to earth axes
$T_f, T_v$		Kinetic energy of fluid and vehicle, respectively





$u, v, w$	$u' = u/\bar{U}$	Longitudinal, transverse and normal components, respectively of the velocity of the origin of body axes relative to the fluid
-----------	------------------	---

$\dot{u}, \dot{v}, \dot{w}$	$\dot{u}' = \dot{u}l/\bar{U}^2$	Longitudinal, transverse and normal components, respectively of the acceleration of the origin of body axes relative to the fluid
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$U$	$U' = U/\bar{U} = 1$	Velocity of origin of body axes relative to the fluid
-----	----------------------	---

$\bar{V}$	$\bar{V}' = \bar{V}/l^3$	Volume of submersible
-----------	--------------------------	-----------------------

$W$	$W' = W/\frac{\rho}{2} l^2 \bar{U}^2$	Weight of submersible
-----	---------------------------------------	-----------------------

$x, y, z$	$x' = x/l$	Body axes, or coordinates of a point relative to body axes
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$x_B, y_B, z_B$	$x'_B = x_B/l$	Coordinates of the center of buoyancy relative to body axes
-----------------	----------------	---

$x_G, y_G, z_G$	$x'_G = x_G/l$	Coordinates of the center of gravity relative to body axes
-----------------	----------------	--



$$x_o, y_o, z_o \quad x'_o = x_o/l$$

Fixed or inertial axes, or  
coordinates of a point rela-  
tive to fixed axes

$$\dot{x}_E, \dot{y}_E, \dot{z}_E \quad \dot{x}'_E = \dot{x}_E/U$$

Longitudinal, transverse and  
normal components, respective-  
ly of the velocity of the or-  
igin of body axes relative  
to the inertial axes

$$X, Y, Z \quad X' = X/\frac{1}{2}\rho l^2 U^2$$

Longitudinal, lateral and  
normal components, respec-  
tively, of hydrodynamic  
force on the submersible

$$X_u \quad X'_{\dot{u}} = X_u/\frac{1}{2}\rho l^2 U = \partial X'/\partial \dot{u}'$$

Typical static force deriv-  
ative of a force component  
with respect to a velocity  
component,  $\partial X/\partial u$

$$X_{\ddot{u}} \quad X'_{\ddot{u}} = X_{\dot{u}}/\frac{1}{2}\rho l^3 = \partial X'/\partial \ddot{u}'$$

Typical inertia coefficient;  
derivative of a force compon-  
ent with respect to an accel-  
eration component,  $\partial X/\partial \ddot{u}$

$$X_p \quad X'_{\dot{p}} = X_p/\frac{1}{2}\rho l^3 U = \partial X'/\partial \dot{p}'$$

Typical rotary force deriv-  
ative; derivative of a force  
component with respect to an  
angular velocity component,  
 $\partial X/\partial \dot{p}$





$$X_p = X_p / \frac{1}{2} \rho l^4 = \partial X' / \partial \dot{p}$$

Typical inertia coefficient;  
derivative of a force component with respect to an angular acceleration component,  $\partial X / \partial \dot{p}$

$$X_{uw} = X_{uw} / \frac{1}{2} \rho l^2 = \partial^2 X' / \partial u \partial w$$

Typical second order force coefficient; derivative of a force component with respect to the square of a velocity component or the product of two velocity components,  $\partial^2 X / \partial u \partial w$

$$X_{vr} = X_{vr} / \frac{1}{2} \rho l^3 = \partial^2 X' / \partial v \partial r$$

Typical second order force coefficient; derivative of a force component with respect to the product of a velocity component,  $\partial^2 X / \partial v \partial r$

$$X_{rp} = X_{rp} / \frac{1}{2} \rho l^4 = \partial^2 X' / \partial r \partial p$$

Typical second order force coefficient; derivative of a force component with respect to the square of an angular velocity component or the product of two angular velocity components,  $\partial^2 X / \partial r \partial p$



$X_{EFF}$	$X'_{EFF} = X_{EFF} / \frac{1}{2} \rho l^2 U^2$	Typical effector force coefficient
$Y_*, Z_*$	$Y'_* = Y'_* / \frac{1}{2} \rho l^2 U^2$	Lateral and normal forces when body angles $(\alpha, \beta)$ and control surface angles are zero
$\alpha, \beta$		Angles of attack and drift, respectively
$\gamma$		Specific weight of the fluid
$\theta, \psi, \phi$		Angles of pitch, yaw and roll respectively
$\rho$		Mass density of the fluid
$\rightarrow$	Vector	
$\cdot$	Time derivative $\partial/\partial t$	
$'$	Non-dimensionalized parameter	
$[M]$	Matrix	
$\partial$	Partial derivative	
$d$	Derivative	



## INTRODUCTION

An important operating mode of deep submersibles is the ascending and descending mode. Unlike large high speed military submarines which ascend and descend dynamically by use of a combination of speed and appendage deflection, deep submersibles depend partially and sometimes entirely, as in the case of the TRIESTE, upon buoyant ascent and descent. Of the ascending and descending operations, the most critical is during an emergency ascent in which most or all of the jettisonable weights are removed from the vehicle in order to obtain as rapid an ascent as possible.

The majority of deep submersibles fall into a class of vehicles characterized by low speed and minimal appendage streamlining. They are designed for underwater research and rescue missions which do not, except for the travel mode of the Deep Submergence Rescue Vehicle, require large speeds. They are equipped with many and diverse appendages for accomplishing their missions such as manipulator arms, lights, propulsion motors, sampling equipment, TV cameras and mating skirts, all of which effect, to varying degrees, the streamlining and hydrodynamics of these vehicles.

In order to study the motions and ascent trajectories of submersibles in normal or emergency ascent without model or full scale tests, it is necessary to develop a mathematical model of the vehicle which can accomodate the effects of varying mass and center of mass.

This work is an attempt to develop the mathematical model using a set of second order equations of motion, and solve these equations by use of a high speed digital computer.

The primary sources of material for this work are the works of Abkowitz, Dogan, Gertler and Hagen, Lamb and Strumpf, but the secondary



sources, acknowledged or not, are no less important of the development of this work.

The problem of determining the motions of a totally submerged body has been treated by many authors, however, there appear to be only two basic means for arriving at these equations. These are by energy methods and by vector calculus.

The first method is that used by Sir Horace Lamb in his book "Hydrodynamics" which first appeared in 1879 (see ref 1). The energy method is based upon the existence of a single valued velocity-potential which implies that the motion of the fluid is entirely due to that of the submersible, and is therefore irrotational and acyclic. This method leads to a completely general set of equations representing the rigid body dynamics, but the hydrodynamic forces that result represent only the so called added mass or added inertia effects and not all the forces acting on the body. Of the forces that are missing the most important are those due to circulation, separation and vortex shedding.

The second method of developing the equations of motion is to combine a vector expansion of Newton's laws of motion, expressed as follows:

$$\vec{F} = \frac{d}{dt} \text{ (Momentum) } = \text{the vector force acting on the body} \quad (1)$$

$$\vec{H} = \frac{d}{dt} \text{ (Angular momentum) } = \text{the vector moment acting on the body} \quad (2)$$

with a Taylor series expansion of the hydrodynamic forces and moments expressed as:

$$\begin{matrix} \text{Forces} \\ \text{Moments} \end{matrix} = f \left( \begin{matrix} \text{Properties of body; Properties of motion,} \\ \text{Properties of fluid} \end{matrix} \right) \quad (3)$$





which reduces to

$$\frac{\vec{F}}{H} = f \text{ (Properties of motion)} \quad (4)$$

for a particular vehicle in a particular fluid. This method has been used by A. Strumpf in 1960 in developing his "Equations of Motion of a Submerged Body with Varying Mass" (see ref 2) and by Prof. M. A. Abkowitz in 1949 in his lecture course and notes on "The Dynamical Stability of Submarines" (see ref's 3 and 10). It too results in a completely general set of equations describing the rigid body dynamics, but its greatest asset lies in the generality of the hydrodynamic forces and moments. The hydrodynamic forces and moments obtained from a Taylor series expansion include not only all the added mass effects but also the circulation, separation and vortex shedding effects. The only limitation on this method is the availability of theoretical or experimental data to use in the equations.

From the preceding discussion and equations (1 through 4), it is obvious that the derivation of the rigid body motion may be completely separated from the problem of developing a suitable form for the hydrodynamic effects. Therefore, the two methods of development may be broken down and part of each used.

This work shall attempt to take advantage of the simplicity of the energy development of the rigid body dynamics, while retaining the generality provided by the Taylor series expansion of the hydrodynamic forces and moments.

The solution of the equations of motion that will be developed employs a technique suggested in 1964 by G. Parascis in his solution of linearized equations of motion for heave and pitch of a ship (see ref 4)



and again in 1967 by L. M. McCloskey for the digital simulation of the DSRV control system and autopilot (see ref 5).

The coefficients used to test the solution of the equations of motion come from a series of model experiments conducted on the DSRV. The results of the computer solution will not, however, be the ascent trajectory for the DSRV since there is an assumption, in this work, of zero propulsion forces in the development of the equations of motion.

The assumptions and the statement of the problem are given in Chapter I, the equations of motion are derived in Chapter II and a method for solving the equations of motion is developed in Chapter III.



## CHAPTER I

### FORMULATION OF THE PROBLEM

The problem involves a deep submersible vehicle of given geometry and dimensions which is in free ascent through a stationary fluid.

#### I - 1 Assumptions

The vehicle is assumed to be a rigid body with no elastic deformations of a vibratory nature. It has six degrees of freedom, three translational and three rotational. We shall be interested in motions in both the horizontal and vertical planes of motion. Velocities are small. Hydrodynamic effects of second order in acceleration shall be considered negligible. The only body symmetry is port and starboard.

##### I - 1.1

The neglecting of vibratory motions is reasonable since the frequencies of vibration of the hull acting as an elastic body are of different orders of magnitude than the frequencies of motion and do not excite the latter. Elastic deformations due to vehicle compressability must be included since they directly affect the buoyancy of the vehicle.

##### I - 1.2

The interest in both planes of motion is due to the desire for as general a set of equations as possible.

##### I - 1.3

The assumption of small velocities is realistic in that free ascent velocities and open ocean currents are in general of order less than ten knots.



#### I - 1.4

The use of a set of second order equations of motion is deemed necessary to appropriately describe the hydrodynamic cross-coupling that takes place in a problem such as this. The second order acceleration effects are assumed to be zero on the basis of potential theory (see ref 1). This, however, has not been experimentally verified.

#### I - 1.5

Neglecting assymetries due to relatively small appendages which are not control surfaces, there are few vehicles which operate in the ocean environment which do not possess port and starboard symmetry. For this reason the assumption of port and starboard symmetry has been made.

#### I - 2 Initial and Other Conditions

The vehicle is to be initially at rest relative to the inertial, earth fixed, axes. The control effectors, propellers, thrusters, rudders, dive planes, etc., are inoperable and/or in neutral position. The driving force for the vehicle shall be a decrease in weight due to jettisoning of ballast or an increase in volume due to vehicle decompression as it rises.

These conditions, though arbitrary, serve to restrict the problem to one of manageable size.





## CHAPTER II

### EQUATIONS OF MOTION

#### II - 1 General:

The derivation of the equations of motion for a rigid body in six degrees of freedom with a varying mass and center of mass follows closely that of Dr. Pierre Dogan in reference (5), which is based primarily upon the development of the equations of motion by Lamb in reference (1). The derivation of the hydrodynamic force equations follows that of Professor Martin Abkowitz in reference (3) except that, in this work, the second order terms are retained. The forces due to gravity are determined using the transformations set forth in reference (6) and the angular velocity transformations given by Professor Abkowitz in reference (7).

The axis systems necessary to describe the motions of a body and its trajectory through a fluid include a body fixed system and an inertial system.

#### II - 2 Axis Systems

The equations of motion for an ascending vehicle must be written in an earth fixed axis system in order to determine the trajectory of the vehicle relative to some fixed point. An additional body fixed system is required in order to describe the hydrodynamic interactions between the vehicle and the water.

##### II - 2.1 Inertial Axis System

The right-handed earth fixed axis system,  $A_E$  (see figure II.1), is assumed to be an inertial system for the reason that the accelerations



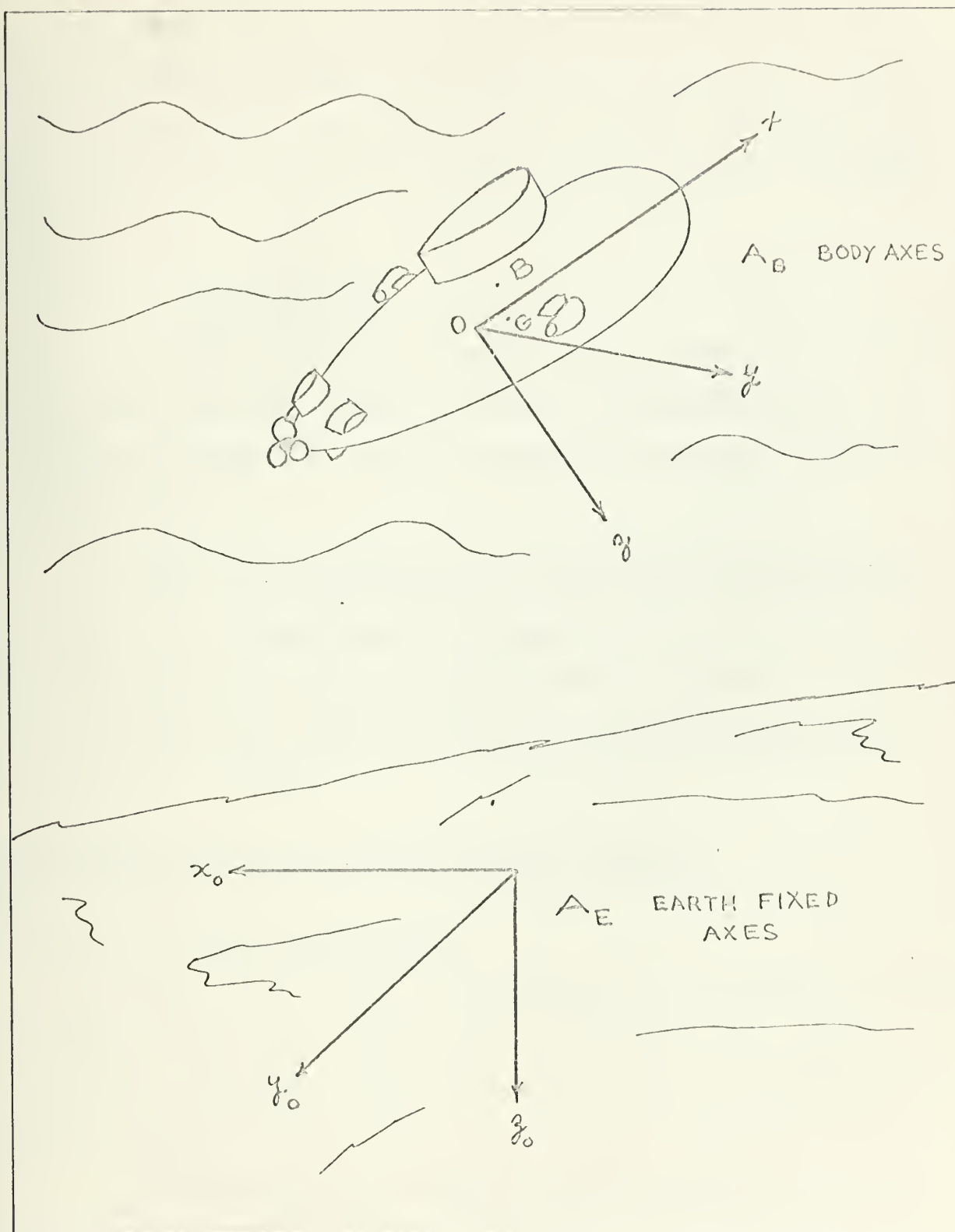


Figure 1 Coordinate Systems



of a point on the surface of the earth are an order of magnitude smaller than those which are of importance to the motions of the vehicle.  $A_E$  is an orthogonal set of axes fixed relative to the earth such that components  $x_E$  and  $y_E$  are in a horizontal plane, and the  $z_E$  axis is vertical and directed downwards.

## II - 2.2 Body Axis System

The right-handed body axis system,  $A_B$  (see figure II.1), is fixed in the vehicle such that advantage is taken of the assumed principal plane of symmetry by placing the origin of the system in this plane. The axes of this system are:

- x axis - the longitudinal axis, directed from the after to the forward end of the vehicle,
- y axis - the transverse axis, directed to starboard,
- z axis - the normal axis, directed from top to bottom (deck to keel).

The xz plane is the assumed principal plane of symmetry.

## II - 2.3 Body Axes Orientation

Angular displacements of  $A_B$  relative to  $A_E$  are specified by a set of modified 'Euler angles' which are taken as positive in the sense of rotation of a right-handed screw advancing in the positive direction of the axis of rotation.

The orientation of  $A_B$  relative to  $A_E$  is described in terms of a roll angle  $\phi$ , a pitch angle  $\theta$  and a yaw angle  $\psi$ . Before defining these angles, an order of rotations must be chosen since finite rotations are not true vector quantities and do not obey the rules for adding vectors. The



order chosen here conforms to that set forth in reference (6) which is:

- (1) rotate about the initial  $z = z_E$  axis through an angle of yaw  $\psi$ ,
- (2) rotate about the new position of the  $y = y_1$  axis through an angle of pitch  $\theta$ ,
- (3) finally rotate about the new position of the  $x = x$  axis through an angle of roll  $\phi$ .

In accordance with the order of rotations above we have the following definitions:

$\theta$  - the angle of pitch; the angle of elevation of the  $x$  axis; the angle between the  $x$  axis and the horizontal plane  $x_E y_E$ ,

$\psi$  - the angle of yaw; the angle from the vertical plane  $x_E z_E$  to the vertical plane  $xz_E$ ,

$\phi$  - the angle of roll; the angle from the vertical  $xz_E$  plane to the principal plane of symmetry  $xz$ .

The successive rotations required to specify the orientation of the body axes relative to the earth fixed axes can be described by three orthogonal matrices  $[\psi]_{z_E}$ ,  $[\theta]_{y_1}$ ,  $[\phi]_x$ :

$$[\psi]_{z_E} = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[\theta]_{y_1} = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$





$$\begin{bmatrix} \phi \end{bmatrix}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix}$$

Unit vectors in  $A_B$  and  $A_E$  are related by an orthogonal matrix:

$$\begin{bmatrix} i_B \\ j_B \\ k_B \end{bmatrix} = T_B \begin{bmatrix} i_E \\ j_E \\ k_E \end{bmatrix}$$

where  $T_B$  is the product of the three orthogonal matrices defining the rotations:

$$T_B = \begin{bmatrix} \phi \end{bmatrix}_x \begin{bmatrix} \theta \end{bmatrix}_{y_1} \begin{bmatrix} \psi \end{bmatrix}_{z_E}$$

$$= \begin{bmatrix} \cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\ -\cos \phi \sin \psi & \cos \phi \cos \psi & \sin \phi \cos \theta \\ +\sin \phi \sin \theta \cos \psi & +\sin \phi \sin \theta \sin \psi & \cos \phi \cos \theta \\ \sin \phi \sin \psi & -\sin \phi \cos \psi & \cos \phi \cos \theta \\ +\sin \theta \cos \phi \cos \psi & +\cos \phi \sin \theta \sin \psi & \end{bmatrix}$$

Velocities in  $A_B$  and  $A_E$  are also related by the transformation matrix  $T_B$ :

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = T_B \begin{bmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{bmatrix}$$

The vehicle angular velocities in  $A_B$  and  $A_E$  are, however, related by a non-orthogonal matrix, which is the sum of three components along the  $z_E$ ,  $y_1$  and  $x$  axes of magnitude  $\dot{\psi}$ ,  $\dot{\theta}$  and  $\dot{\phi}$ .



$$\begin{aligned}
\begin{bmatrix} p \\ q \\ r \end{bmatrix} &= \begin{bmatrix} \phi \end{bmatrix}_x \begin{bmatrix} 0 \end{bmatrix}_{y_1} + \begin{bmatrix} \phi \end{bmatrix}_x \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ 0 \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & -\sin \theta \\ 0 & \cos \phi & \cos \theta \sin \phi \\ 0 & -\sin \phi & \cos \theta \cos \phi \end{bmatrix} \cdot \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \\
&= T_A \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}
\end{aligned}$$

### II - 3 Conservation of Momentum Equations

The derivation of the dynamical equations for a vehicle with a varying mass and center of mass have been treated in two different manners by:

- (1) Albert Strumpf of Davidson Lab, (see ref 2) using vector calculus, and including variations in mass, moments of inertia and CG position.
- (2) Pierre Dogan of MIT Instrumentation Lab, (see ref 5), using a Lagrangian formalism, including time variation of the inertial tensor, and making assumptions as to the form of the movable weights.

The treatment by Strumpf assumes a body that is a rocket, so that mass is discharged from the body. The treatment by Dogan, for the Deep Submergence Rescue Vehicle (DSRV), assumes that the mass of the body is constant but allows the position of the center of gravity to change.

The development by Dogan avoids the long vectorial derivations



involved in Strumpf's development, while sacrificing generality by not including a change in mass. This feature could be included if it were desired and so the approach by Dogan will be used.

Nine generalized velocities and coordinates are sufficient to describe the motions of the vehicle. These are: six velocities ( $u, v, w, p, q, r$ ) to describe the vehicle and three coordinates ( $x_G, y_G, z_G$ ) to describe the motion of the center of gravity. The following six Lagrange equations will give the needed vehicle momentum equations. (See Lamb, "Hydrodynamics" 6th Ed, page 168)

$$\frac{d}{dt} \frac{\partial T_v}{\partial u} - r \frac{\partial T_v}{\partial v} + q \frac{\partial T_v}{\partial w} = X \quad (2.3 - 1)$$

$$\frac{d}{dt} \frac{\partial T_v}{\partial v} - p \frac{\partial T_v}{\partial w} + r \frac{\partial T_v}{\partial u} = Y \quad (2.3 - 2)$$

$$\frac{d}{dt} \frac{\partial T_v}{\partial w} - q \frac{\partial T_v}{\partial u} + p \frac{\partial T_v}{\partial v} = Z \quad (2.3 - 3)$$

$$\frac{d}{dt} \frac{\partial T_v}{\partial p} - w \frac{\partial T_v}{\partial v} + v \frac{\partial T_v}{\partial w} - r \frac{\partial T_v}{\partial q} + q \frac{\partial T_v}{\partial r} = K \quad (2.3 - 4)$$

$$\frac{d}{dt} \frac{\partial T_v}{\partial q} - u \frac{\partial T_v}{\partial w} + w \frac{\partial T_v}{\partial u} - p \frac{\partial T_v}{\partial r} + r \frac{\partial T_v}{\partial p} = M \quad (2.3 - 5)$$

$$\frac{d}{dt} \frac{\partial T_v}{\partial r} - v \frac{\partial T_v}{\partial u} + u \frac{\partial T_v}{\partial v} - q \frac{\partial T_v}{\partial p} + p \frac{\partial T_v}{\partial q} = N \quad (2.3 - 6)$$

$T_v$  is the vehicle total kinetic energy.  $X, Y, Z, K, M, N$  are the generalized forces and moments of which some can be further described by a potential function and others represent friction and drag.

The three Lagrange equations necessary to describe the momentum balance equation for the jettisonable ballast subsystem are assumed to reduce to quasi-steady equations defining the CG location from the integrals of the various ballast release rates.

This procedure is as much a necessity as it is a simplification



since, in the case of dropping ballast, the ballast may take almost any form from liquid mercury and iron shot to large blocks of metal or pieces of equipment. The dropping of a liquid or a granular solid can be reasonably modeled as a function of time but the dropping of chunks of metal or pieces of equipment would create singularities in a functional relationship. The obvious answer would be to use a combination of a smooth function and steps to obtain a reasonably accurate model of the deballasting of a vehicle.

There is one additional factor which also affects the decision to reduce the function to a quasi-steady process. The total ballast dropped is no more than three percent of the total vehicle weight and the rate at which it is removed is of order .3 percent of the total vehicle weight per second. This would then say that any Taylor series expansion of this function, which retained terms commensurate with the second order expansion to be used in obtaining the hydrodynamic forces, would contain at most the linear terms.

The effect of such an approximation is entirely dependent upon the length of the time interval over which the process is assumed to be steady and shall be discussed in conjunction with the computer program. Suffice it to say here, that until accurate model tests can be conducted, the effect of this assumption is truly unknown, but appears to be of inconsequential magnitude.

The equations describing the variable position of the CG in the body axis system are:





$$x_G = \frac{x_{GB} W - \sum_{i=1}^N x_i \int_{t_0}^t W_i dt}{W - \sum_{i=1}^N W_i} \quad (2.3 - 7)$$

$$y_G = \frac{y_{GB} W - \sum_{i=1}^N y_i \int_{t_0}^t W_i dt}{W - \sum_{i=1}^N W_i} \quad (2.3 - 8)$$

$$z_G = \frac{z_{GB} W - \sum_{i=1}^N z_i \int_{t_0}^t W_i dt}{W - \sum_{i=1}^N W_i} \quad (2.3 - 9)$$

where  $x_{GB}$ ,  $y_{GB}$ ,  $z_{GB}$  are the components of the CG of the vehicle with all of the ballast,  $W$  is the vehicle weight including all jettisonable ballast,  $x_i$ ,  $y_i$ ,  $z_i$  are the CG's of the  $N$  jettisonable ballast weights  $W_i$ .

The vehicle kinetic energy is the sum:

$$T_v = \frac{m}{2} \vec{V}_G^2 + \frac{1}{2} \vec{\omega} I_G \vec{\omega} \quad (2.3 - 10)$$

where  $m$ ,  $\vec{V}_G$ ,  $I_G$  and  $\vec{\omega}$  are the vehicle mass, the CG velocity, the inertial tensor about the CG and the angular velocity vector. Defining axes  $x'$ ,  $y'$ ,  $z'$  through the CG parallel to the vehicle body axes, one has

$$I_G = \begin{bmatrix} I_{x'x'} & I_{x'y'} & I_{x'z'} \\ I_{y'x'} & I_{y'y'} & I_{y'z'} \\ I_{z'x'} & I_{z'y'} & I_{z'z'} \end{bmatrix} \quad (2.3 - 11)$$

where  $I_{x'x'}$ ,  $I_{y'y'}$ , ..... have the usual meanings:



$$I_{x'x'} = \iiint_V (y'^2 + z'^2) \, dm$$

$$I_{x'y'} = \iiint_V (x'y') \, dm$$

Computing the components of  $\vec{V}_G$  in body axes one has:

$$\vec{V}_G = (u + qz_G - ry_G + \dot{x}_G, v + rx_G - pz_G + \dot{y}_G, w + py_G - qx_G + \dot{z}_G) \quad (2.3 - 12)$$

Substituting (2.3 - 11) and (2.3 - 12) into (2.3 - 10) one gets the kinetic energy  $T_v$  and its partial derivatives:

$$\frac{\partial T_v}{\partial u} = m (u + qz_G - ry_G + \dot{x}_G) \quad (2.3 - 13)$$

$$\frac{\partial T_v}{\partial v} = m (v + rx_G - pz_G + \dot{y}_G) \quad (2.3 - 14)$$

$$\frac{\partial T_v}{\partial w} = m (w + py_G - qx_G + \dot{z}_G) \quad (2.3 - 15)$$

$$\begin{aligned} \frac{\partial T_v}{\partial p} &= I_{x'x'} p + I_{x'y'} q + I_{x'z'} r \\ &\quad - m z_G (v + rx_G - pz_G + \dot{y}_G) \\ &\quad + m y_G (w + py_G - qx_G + \dot{z}_G) \end{aligned} \quad (2.3 - 16)$$

$$\begin{aligned} \frac{\partial T_v}{\partial q} &= I_{y'y'} q + I_{y'z'} r + I_{y'x'} p \\ &\quad - m x_G (w + py_G - qx_G + \dot{z}_G) \\ &\quad + m z_G (u + qz_G - ry_G + \dot{x}_G) \end{aligned} \quad (2.3 - 17)$$

$$\begin{aligned} \frac{\partial T_v}{\partial r} &= I_{z'z'} r + I_{z'x'} p + I_{z'y'} q \\ &\quad - m y_G (u + qz_G - ry_G + \dot{x}_G) \\ &\quad + m x_G (v + rx_G - pz_G + \dot{y}_G) \end{aligned} \quad (2.3 - 18)$$



The inertial tensor  $I_G$  about the CG can be algebraically related to the inertial tensor  $I_O$  about the origin (defined in  $x, y, z$ ) and the distance  $x_G, y_G, z_G$ . For example:

$$I_{xx} = I_{x'x'} + m (z_G^2 + y_G^2)$$

$$I_{xy} = I_{x'y'} - mx_G y_G$$

Substituting these for the inertial tensor,  $I_G$ , equations (2.3 - 16) through (2.3 - 18) become:

$$\begin{aligned} \frac{\partial T_V}{\partial p} &= I_{xx} p + I_{xy} q + I_{xz} r \\ &- mz_G (v + \dot{y}_G) \\ &+ my_G (w + \dot{z}_G) \end{aligned} \quad (2.3 - 19)$$

$$\begin{aligned} \frac{\partial T_V}{\partial q} &= I_{yy} q + I_{yz} r + I_{yx} p \\ &- mx_G (w + \dot{z}_G) \\ &+ mz_G (u + \dot{x}_G) \end{aligned} \quad (2.3 - 20)$$

$$\begin{aligned} \frac{\partial T_V}{\partial r} &= I_{zz} r + I_{zx} p + I_{zy} q \\ &- my_G (u + \dot{x}_G) \\ &+ mx_G (v + \dot{y}_G) \end{aligned} \quad (2.3 - 21)$$

Substituting these equations and equations (2.3 - 13) through (2.3 - 15) (without primed subscripts) into the Lagrangian equations of motion (2.3 - 1) through (2.3 - 6), one gets the dynamical equations:



$$\begin{aligned}
X = m \left[ \dot{u} - rv + qw - x_G (q^2 + r^2) + y_G (pq - \dot{r}) + z_G (pr + \dot{q}) \right. \\
\left. + 2q\dot{z}_G - 2r\dot{y}_G + \ddot{x}_G \right] \quad (2.3 - 22)
\end{aligned}$$

$$\begin{aligned}
Y = m \left[ \dot{v} - pw + ru - y_G (r^2 + p^2) + z_G (qr - \dot{p}) + x_G (qp + \dot{r}) \right. \\
\left. + 2r\dot{x}_G - 2p\dot{z}_G + \ddot{y}_G \right] \quad (2.3 - 23)
\end{aligned}$$

$$\begin{aligned}
Z = m \left[ \dot{w} - qu + pv - z_G (p^2 + q^2) + x_G (rp - \dot{q}) + y_G (rq + \dot{p}) \right. \\
\left. + 2p\dot{y}_G - 2q\dot{x}_G + \ddot{z}_G \right] \quad (2.3 - 24)
\end{aligned}$$

$$\begin{aligned}
K = I_{xx} \dot{p} + I_{xy} (\dot{q} - pr) + I_{xz} (\dot{r} + pq) + I_{yz} (q^2 - r^2) + (I_{zz} - I_{yy}) qr \\
- mz_G (\dot{v} - pw + ru + r\dot{x}_G + \dot{y}_G) \\
+ my_G (\dot{w} - qu + pv - q\dot{x}_G + \dot{z}_G) \\
+ \dot{I}_{xx} p + \dot{I}_{xy} q + \dot{I}_{xz} r + mx_G (\dot{z}_G r + \dot{y}_G q) \quad (2.3 - 25)
\end{aligned}$$

$$\begin{aligned}
M = I_{yy} \dot{q} + I_{yz} (\dot{r} - qp) + I_{yx} (\dot{p} + qr) + I_{zx} (r^2 - p^2) + (I_{xx} - I_{zz}) rp \\
- mx_G (\dot{w} - qu + pv + p\dot{y}_G + \dot{z}_G) \\
+ mz_G (\dot{u} - rv + qw - r\dot{y}_G + \dot{x}_G) \\
+ \dot{I}_{yy} q + \dot{I}_{yz} r + \dot{I}_{yx} p + my_G (\dot{x}_G p + \dot{z}_G r) \quad (2.3 - 26)
\end{aligned}$$

$$\begin{aligned}
N = I_{zz} \dot{r} + I_{zx} (\dot{p} - rq) + I_{zy} (\dot{q} + rp) + I_{xy} (p^2 - q^2) + (I_{yy} - I_{xx}) pq \\
- my_G (\dot{u} - rv + qw + q\dot{z}_G + \dot{x}_G) \\
+ mx_G (\dot{v} - pw + ru - p\dot{z}_G + \dot{y}_G) \\
+ \dot{I}_{zz} r + \dot{I}_{zx} p + \dot{I}_{zy} q + mz_G (\dot{y}_G q + \dot{x}_G p) \quad (2.3 - 27)
\end{aligned}$$





where  $I_{xx}, I_{xy}, \dots$  are about axes through the vehicle origin. These equations also contain derivatives of the form  $\dot{I}_{xx}, \dot{I}_{xy}, \dots, \dot{x}_G, \dot{y}_G, \dots$

The tensor  $I_0$  can be thought of as being made up of two parts; a constant part representing the vehicle with all jettisonable ballast removed,  $I_1$ , and the jettisonable ballast,  $I_2$ , such that:

$$I_0 = I_1 + I_2 \quad (2.3 - 28)$$

The contribution of the ballast can be modeled by assuming that each weight that is part of the jettisonable ballast is lumped at its center of gravity  $(x_{gi}, y_{gi}, z_{gi})$ .

Then:

$$I_{xx,2} = \sum_{i=1}^N m_i (y_{gi}^2 + z_{gi}^2) \quad (2.3 - 29)$$

$$I_{xy,2} = \sum_{i=1}^N m_i x_{gi} y_{gi} \quad (2.3 - 30)$$

$$I_{xz,2} = \sum_{i=1}^N m_i x_{gi} z_{gi} \dots \quad (2.3 - 31)$$

where  $N$  is the number of weights.

$I_2$  is the time varying part of  $I_0$ , however, to be consistent with the quasi-steady approximation made in developing equations (2.3 - 7 through 2.3 - 9), a quasi-steady change in the inertial tensor must also be assumed. This then says that the terms involving time derivatives of the inertial tensor and the center of gravity can be dropped, since they are zero during the time interval over which the process is assumed to be steady.

The equations can be further reduced when it is recognized that,



due to the assumption of an xz plane of symmetry and a further assumption that the ballast will be dropped symmetrically, the products of inertia

$$I_{xy,1} = I_{yx,1} = I_{yz,1} = I_{zy,1} = I_{xy,2} = I_{yx,2} = I_{yz,2} = I_{zy,2} = 0$$

Thus, the total moment of inertia becomes quasi-steady and can be used in the equations of motion without 0, 1 or 2 subscripts. The final form of the dynamical equations then becomes:

$$X = m \left[ \dot{u} - rv + qw - x_G (q^2 + r^2) + y_G (pq - \dot{r}) + z_G (pr + \dot{q}) \right] \quad (2.3 - 32)$$

$$Y = m \left[ \dot{v} - pw + ru - y_G (r^2 + p^2) + z_G (qr - \dot{p}) + x_G (qp + \dot{r}) \right] \quad (2.3 - 33)$$

$$Z = m \left[ \dot{w} - qu + pv - z_G (p^2 + q^2) + x_G (rp - \dot{q}) + y_G (rq + \dot{p}) \right] \quad (2.3 - 34)$$

$$K = I_{xx} \dot{p} + I_{xz} (\dot{r} + pq) + (I_{zz} - I_{yy}) qr + m \left[ -z_G (\dot{v} - pw + ru) + y_G (\dot{w} + pv - qu) \right] \quad (2.3 - 35)$$

$$M = I_{yy} \dot{q} + I_{zx} (r^2 - p^2) + (I_{xx} - I_{zz}) rp + m \left[ -x_G (\dot{w} - qu + pv) + z_G (\dot{u} + qw - rv) \right] \quad (2.3 - 36)$$

$$N = I_{zz} \dot{r} + I_{zx} (\dot{p} - rq) + (I_{yy} - I_{xx}) pq + m \left[ -y_G (\dot{u} - rv + qw) + x_G (\dot{v} + ru - pw) \right] \quad (2.3 - 37)$$

where  $m$ ,  $x_G$ ,  $y_G$ ,  $z_G$ ,  $I_{xx}$ ,  $I_{yy}$ ,  $I_{zz}$ ,  $I_{xz}$  are all quasi-steady functions of time.

The forcing terms for the hydrodynamic equations are made up of



gravity forces, hydrodynamic forces and propulsion induced forces. Since the problem has been defined as a free ascent problem there will be no propulsion forces included. Because of this restriction, the experimental hydrodynamic coefficients should be obtained without propellers running. The total forcing terms are then:

$$\begin{aligned}
 X &= X_G + X_H \\
 Y &= Y_G + Y_H \\
 Z &= Z_G + Z_H \\
 K &= K_G + K_H \\
 M &= M_G + M_H \\
 N &= N_G + N_H
 \end{aligned}
 \tag{2.3 - 38}$$

## II - 4 Gravity Forces

The hydrostatic pressure field induced by gravity creates a buoyancy force  $B$  through the CB. This force varies with ambient water density and vehicle volume. The instantaneous weight of the body,  $W$ , acting through the CG, is made up of  $W_B$ , the weight of the body without jettisonable ballast, less  $W_i$ , the weight of the ballast components removed.

During the initial phase of the ascent the items in  $\sum_{i=1}^N W_i$  are increased until all of the ballast components have been removed, at this point the buoyant force  $(-B + W)$  becomes a maximum, if we neglect changes in vehicle volume and density. This maximum force is sustained for the rest of the ascent.

The instantaneous buoyant force can thus be represented by:

$$-B + W = \sum_{i=1}^N W_i
 \tag{2.4 - 1}$$

where  $N$  = the number of ballast components removed. This force acts



upwards along the local vertical. Due to the choice of origin of the body axes, the gravity induced torque is  $\vec{r}_G \times \vec{B}$  where  $\vec{r}_G$  is the CG position vector in body axes and  $\vec{B}$  is the vehicle buoyancy vector acting up along the local vertical. Resolving along body axes the gravity forces become:

$$X_G = - (W - B) \sin \theta \quad (2.4 - 2)$$

$$Y_G = (W - B) \cos \theta \sin \phi \quad (2.4 - 3)$$

$$Z_G = (W - B) \cos \theta \cos \phi \quad (2.4 - 4)$$

$$K_G = (y_G^W - y_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \cos \theta \sin \phi \quad (2.4 - 5)$$

$$M_G = - (x_G^W - x_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \sin \theta \quad (2.4 - 6)$$

$$N_G = (x_G^W - x_B^B) \cos \theta \sin \phi + (y_G^W - y_B^B) \sin \theta \quad (2.4 - 7)$$

## II - 5 Hydrodynamic Forces

The hydrodynamic forces and moments that act on a body moving through a real fluid are the result of:

- (1) hydrodynamic inertial affects (linear added mass terms),
- (2) skin friction, separation and cross-flow drag effects,
- (3) circulation effects.

These effects are all functions of the velocities and accelerations of the body. Therefore, the hydrodynamic forces and moments can be expressed functionally as:

$$\begin{Bmatrix} F_H \\ L_H \end{Bmatrix} = f(u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}) \quad (2.5 - 1)$$

This function may be reduced to a workable form by expanding the function in a Taylor series. Expanding the function in this form requires that the function and its derivatives be continuous in the region of the





values of the variables under consideration. A typical second order expansion of one of the force equations would be of the form:

$$\begin{aligned}
 X = X_0 &+ u \frac{\partial X}{\partial u} + v \frac{\partial X}{\partial v} + \dots + r \frac{\partial X}{\partial r} \\
 &+ \dot{u} \frac{\partial X}{\partial \dot{u}} + \dot{v} \frac{\partial X}{\partial \dot{v}} + \dots + \dot{r} \frac{\partial X}{\partial \dot{r}} \\
 &+ \frac{1}{2} (u^2 \frac{\partial^2 X}{\partial u^2} + v^2 \frac{\partial^2 X}{\partial v^2} + \dots + r^2 \frac{\partial^2 X}{\partial r^2} \\
 &+ uv \frac{\partial^2 X}{\partial u \partial v} + uw \frac{\partial^2 X}{\partial u \partial w} + \dots + ur \frac{\partial^2 X}{\partial u \partial r} \\
 &\quad \vdots \\
 &+ pq \frac{\partial^2 X}{\partial p \partial q} + pr \frac{\partial^2 X}{\partial p \partial r} + qr \frac{\partial^2 X}{\partial q \partial r} \\
 &+ u\dot{u} \frac{\partial^2 X}{\partial u \partial \dot{u}} + u\dot{v} \frac{\partial^2 X}{\partial u \partial \dot{v}} + \dots + u\dot{r} \frac{\partial^2 X}{\partial u \partial \dot{r}} \\
 &\quad \vdots \\
 &+ r\dot{u} \frac{\partial^2 X}{\partial r \partial \dot{u}} + \dots + r\dot{r} \frac{\partial^2 X}{\partial r \partial \dot{r}} \\
 &+ \ddot{u} \frac{\partial^2 X}{\partial \dot{u}^2} + \ddot{v} \frac{\partial^2 X}{\partial \dot{v}^2} + \dots + \ddot{r} \frac{\partial^2 X}{\partial \dot{r}^2} \\
 &\quad \vdots \\
 &+ \ddot{p} \frac{\partial^2 X}{\partial \dot{p}^2} + \dots + \ddot{q} \frac{\partial^2 X}{\partial \dot{q}^2} \quad (2.5 - 2)
 \end{aligned}$$

This equation contains ninety-one constant, linear and second order terms arising from the Taylor series expansion. The number of terms, however, can be reduced to thirty-three on the basis of the problem assumptions and restrictions delineated in Chapter I.

The constant term is dropped to conform with the requirement that



initially the only disturbance is due to a buoyant force which is included as a gravity term.

The terms involving products of accelerations with velocities or accelerations are dropped because the second order effects were restricted to velocities only. In addition the results of potential theory indicate that these derivatives are zero. (See ref 2)

After eliminating all but the linear terms and the second order velocity terms, the Taylor series expansions of the hydrodynamic forces and moments become of the form:

$$\begin{aligned}
 X_H = & X_u u + X_v v + X_w w + X_p p + X_q q + X_r r \\
 & + X_{\dot{u}} \dot{u} + X_{\dot{v}} \dot{v} + X_{\dot{w}} \dot{w} + X_{\dot{p}} \dot{p} + X_{\dot{q}} \dot{q} + X_{\dot{r}} \dot{r} \\
 & + X_u^2 u^2 + X_v^2 v^2 + X_w^2 w^2 + X_p^2 p^2 + X_q^2 q^2 + X_r^2 r^2 \\
 & + X_{uv} uv + X_{uw} uw + X_{up} up + X_{uq} uq + X_{ur} ur \\
 & + X_{vw} vw + X_{vp} vp + X_{vq} vq + X_{vr} vr \\
 & + X_{wp} wp + X_{wq} wq + X_{wr} wr \\
 & + X_{pq} pq + X_{pr} pr + X_{qr} qr
 \end{aligned} \tag{2.5 - 3}$$

The terms in this expression are seen to fall into one of three categories, namely:

- (1) added mass or inertial,
- (2) second order non-inertial,
- (3) linear.

In order to further reduce the number of terms retained in each of these cat-



egories, it is necessary to look at the nature of the terms and the effect that a plane of symmetry has on them.

### II - 5.1 Added Mass Terms

A body moving through a real fluid induces a motion in the otherwise stationary fluid because the fluid must move aside and then close in behind the body. As a result of this motion the fluid possesses kinetic energy that it would not possess if the body were not in motion. The added mass terms in the equations take into account the energy given to the fluid by the body.

If the body motion is steady, the related fluid motion is also steady which requires that the kinetic energy be constant. If the kinetic energy is constant, no work is being done on the fluid and therefore the added mass terms may be omitted.

If, however, the body is in accelerated motion, there will be work done by the body on the fluid and it will be necessary to retain at least some of the added mass terms.

Work is accomplished by moving a force through a distance. In the case of a submerged body, the distance is the distance the body travels and the force is the integral over the surface of the body of the pressures exerted by the body on the fluid. This force, in general, represents a system of forces and moments acting on the body which can be obtained from equations (2.3 - 1 through 6), when the kinetic energy is varied.

The kinetic energy of the fluid can be represented as a function of the six velocity components ( $u, v, w, p, q, r$ ). A quadratic form of this function as given by Lamb (see page 172 ref 1) is:



$$\begin{aligned}
2T_f = & Au^2 + Bv^2 + Cw^2 + 2A'vw + 2B'vu + 2C'uv \\
& + Pp^2 + Qq^2 + Rr^2 + 2P'qr + 2Q'rp + 2R'pq \\
& + 2Lup + 2Mvq + 2Nur \\
& + 2F(vr + wq) + 2G(wp + ur) + 2H(uq + vp) \\
& + 2F'(vr - wq) + 2G'(wp - ur) + 2H'(uq - vp) \quad (2.5 - 4)
\end{aligned}$$

where the twenty-one coefficients A, B, C etc. are certain constants determined by the form and position of the surface relative to the co-ordinate axes.

Letting

$$\begin{array}{ll}
F + F' = F_1 & F - F' = F_2 \\
H + H' = H_1 & H - H' = H_2 \\
G + G' = G_1 & G - G' = G_2
\end{array}$$

the last six terms in (2.5 - 4) become:

$$\begin{aligned}
& + 2F_1 vr + G_1 sp + 2H_1 uq \\
& + 2F_2 wq + G_2 ur + 2H_2 vp
\end{aligned}$$

Nine of the coefficients in the above expression may be set to zero if we take advantage of the assumed xz plane of symmetry. Symmetry arguments say that  $T_f$  should not be changed if any of the terms  $vw$ ,  $uv$ ,  $qr$ ,  $pq$ ,  $up$ ,  $vq$ ,  $wr$ ,  $wp$ ,  $ur$  is replaced respectively by  $(-v) w$ ,  $(-v) u$ ,  $(-r) q$ ,  $(-p) q$ ,  $(-p) u$ ,  $(-v) q$ ,  $(-r) w$ ,  $(-p) w$ ,  $(-r) u$ . These terms correspond respectively with the coefficients  $A'$ ,  $C'$ ,  $P'$ ,  $R'$ ,  $L$ ,  $M'$ ,  $N'$ ,  $G$ ,  $G'$ .

When  $T_f$  is substituted for  $T_v$  in equations (2.3 - 1 through 6), these nine coefficients can be traced to their corresponding terms in equations (2.5 - 3), at which time these terms can be eliminated from the





hydrodynamic expressions.

Six partial derivatives must be obtained from equation (2.5 - 4) in order to expand equations (2.3 - 1 through 6), these are:

$$\frac{\partial T_f}{\partial u} = Au + B'w + C'v + Lp + H_1q + G_2r \quad (2.5 - 5)$$

$$\frac{\partial T_f}{\partial v} = Bv + A'w + C'u + M'q + F_1r + H_2p \quad (2.5 - 6)$$

$$\frac{\partial T_f}{\partial w} = Cw + A'v + B'u + N'r + G_1p + F_2q \quad (2.5 - 7)$$

$$\frac{\partial T_f}{\partial p} = Pp + Q'r + R'q + Lu + G_1w + H_2v \quad (2.5 - 8)$$

$$\frac{\partial T_f}{\partial q} = Qq + P'r + R'p + M'v + H_1u + F_2w \quad (2.5 - 9)$$

$$\frac{\partial T_f}{\partial r} = Rr + P'q + Q'p + N'w + F_1v + G_2u \quad (2.5 - 10)$$

These derivatives are then substituted in equations (2.3 - 1 through 6) to obtain:

$$\begin{aligned} X = & Au + B'w + C'v + Lp + H_1q + G_2r \\ & + Cqw + A'vq + B'uq + N'rq + G_1pq + F_2qq \\ & - Bvr - A'wr - C'ur - M'qr - F_1rr - H_2pr \end{aligned} \quad (2.5 - 11)$$

$$\begin{aligned} Y = & Bv + A'w + C'u + M'q + F_1r + H_2p \\ & + Aur + B'wr + C'vr + Lpr + H_1qr + G_2rr \\ & - Cwp - A'vp - B'up - N'rp - G_1pp - F_2qp \end{aligned} \quad (2.5 - 12)$$

$$\begin{aligned} Z = & Cw + A'v + B'u + N'r + G_1p + F_2q \\ & + Bvp + A'wp + C'up + M'qp + F_1rp + H_2pp \\ & - Auq - B'wq - C'vq - Lpq - H_1qq - G_2rq \end{aligned} \quad (2.5 - 13)$$



$$\begin{aligned}
K = & P\dot{p} + Q\dot{r} + R\dot{q} + L\dot{u} + G_1\dot{v} + H_2\dot{v} \\
& + Rrq + P'qq + Q'pq + N'wq + F_1vq + G_2uq \\
& - Qqr - P'rr - R'pr - M'vr - H_1ur - F_2ur \\
& + Cuv + A'vv + B'uv + N'rv + G_1pv + F_2qv \\
& - B'vw - A'uw - C'uv - M'qw - F_1rv - H_2pw
\end{aligned} \tag{2.5 - 14}$$

$$\begin{aligned}
M = & Q\dot{q} + P\dot{r} + R\dot{p} + M\dot{v} + H_1\dot{u} + F_2\dot{u} \\
& + Ppr + Q'rr + R'qr + Lur + G_1wr + H_2vr \\
& - Rrp - P'qp - Q'pp - N'wp - F_1vp - G_2up \\
& + Auw + B'vw + C'vw + Lpw + H_1qw + G_2rw \\
& - Cwu - A'vu - B'uu - N'ru - G_1pu - F_2qu
\end{aligned} \tag{2.5 - 15}$$

$$\begin{aligned}
N = & R\dot{r} + P\dot{q} + N\dot{w} + F_1\dot{v} + G_2\dot{u} \\
& + Qqp + P'rp + R'pp + M'vp + H_1up + F_2wp \\
& - Ppq - Q'rq - R'qq - Luq - G_1wq - H_2vq \\
& + Bvu + A'wu + C'uu + M'qu + F_1ru + H_2pu \\
& - Auv - B'vw - C'vv - Lpv - H_1qv - G_2rv
\end{aligned} \tag{2.5 - 16}$$

Setting the various coefficients in equations (2.5 - 11 through 16) equal to their counterparts in equations (2.5 - 3) it is found that:



$$A' = X_{vq} = -X_{vr} = Y_{\dot{u}} = -Y_{vp} = Z_{\dot{v}} = Z_{vp} = K_{vv} = -K_{vw} = -M_{vu} = N_{wu}$$

$$C' = X_{\dot{v}} = -X_{ur} = Y_{\dot{u}} = Y_{vr} = Z_{up} = -Z_{vq} = -K_{uw} = M_{vw} = N_{uu} = -N_{vv}$$

$$G_1 = X_{pq} = -Y_{pp} = Z_{\dot{p}} = K_{\dot{w}} = K_{pv} = M_{ur} = -M_{pu} = -N_{vq}$$

$$G_2 = X_{\dot{r}} = Y_{rr} = -Z_{rq} = K_{uq} = -M_{up} = M_{rw} = N_{\dot{u}} = -N_{rv}$$

$$L = X_{\dot{p}} = K_{\dot{u}} = M_{ur} = M_{pw} = -N_{uq} = -N_{pv}$$

$$M' = Y_{\dot{q}} = -K_{qw} = M_{\dot{v}} = N_{vp} = N_{qu}$$

$$N' = Z_{\dot{r}} = K_{vq} = -M_{vp} = -N_{ru} = N_{\dot{w}}$$

$$P' = K_{qq} = -K_{rr} = M_{\dot{r}} = M_{qr} = N_{\dot{q}} = N_{rp}$$

$$R' = K_{\dot{q}} = -K_{pr} = M_{\dot{p}} = -M_{qp} = N_{pp} = -N_{qq}$$

$$N' - L' = X_{qr} = K_{vr}$$

$$L - N' = Y_{pr} = M_{ru} = M_{pw}$$

$$M' - L = Z_{pq}$$

$$G_1 + G_2 = M_{rw} = -M_{pu}$$

$$M' - L = N_{vp} = N_{uq} \quad (2.5 - 17)$$

$$H_1 + H_2 = N_{up} = -N_{vq}$$

$$B - A = N_{uv} \quad (2.5 - 18)$$



$$A = X_{\dot{u}} = Y_{ur} = -Z_{uq}$$

$$B = -X_{vr} = Y_{\dot{v}} = Z_{vp}$$

$$C = X_{qw} = -Y_{wp} = Z_{\dot{w}}$$

$$B' = X_{\dot{v}} = X_{uq} = Y_{vr} = -Y_{up} = Z_{\dot{u}} = -Z_{wq} = K_{uv} = M_{vw} = -M_{uu} = -N_{vv}$$

$$P = K_{\dot{p}} = -N_{pq}$$

$$Q = M_{\dot{q}} = N_{qp}$$

$$R = N_{\dot{r}}$$

$$Q' = K_{\dot{r}} = K_{pq} = M_{rr} = -M_{pp} = N_{\dot{p}} = -N_{rq}$$

$$F_1 = -X_{rr} = Y_{\dot{r}} = Z_{rp} = -M_{vp} = N_{\dot{v}} = N_{ru}$$

$$F_2 = X_{qq} = -Y_{qp} = Z_{\dot{q}} = M_{\dot{w}} = -M_{qu} = N_{vp}$$

$$H_1 = X_{\dot{q}} = Y_{qr} = -Z_{qq} = -K_{ur} = M_{\dot{u}} = M_{qw} = N_{up} = -N_{qv}$$

$$H_2 = -X_{pr} = Y_{\dot{p}} = Z_{pp} = K_{\dot{v}} = -K_{pw} = M_{vr} = -N_{vq} = N_{pu}$$

$$C - B = K_{uv}$$

$$F_1 + F_2 = -K_{vr} = K_{vq}$$

$$R - Q = K_{qr}$$

$$P - R = M_{pr}$$

$$A - C = M_{wu}$$

$$Q - P = N_{pq}$$

(2.5 - 18) cont.





where equations (2.5 - 17) represent the terms which are zero due to symmetry.

Eliminating those terms which, due to the xz plane of symmetry, are zero, and using the standard nomenclature, as given in reference (6), in place of Lamb's notation, the added mass expressions become:

$$\begin{aligned} X_{Hi} = & X_{\dot{u}}^{\dot{u}} + X_{\dot{v}}^{\dot{v}} + X_{\dot{q}}^{\dot{q}} + X_{qw}^{qw} + X_{uq}^{uq} \\ & + X_{qq}^{qq} + X_{vr}^{vr} + X_{r^2}^{r^2} + X_{pr}^{pr} \end{aligned} \quad (2.5 - 19)$$

$$\begin{aligned} Y_{Hi} = & Y_{\dot{v}}^{\dot{v}} + Y_{\dot{r}}^{\dot{r}} + Y_{\dot{p}}^{\dot{p}} + Y_{ur}^{ur} + Y_{wr}^{wr} \\ & + Y_{qr}^{qr} + Y_{wp}^{wp} + Y_{up}^{up} + Y_{qp}^{qp} \end{aligned} \quad (2.5 - 20)$$

$$\begin{aligned} Z_{Hi} = & Z_{\dot{v}}^{\dot{v}} + Z_{\dot{u}}^{\dot{u}} + Z_{\dot{q}}^{\dot{q}} + Z_{vp}^{vp} + Z_{rp}^{rp} \\ & + Z_{pp}^{pp} + Z_{uq}^{uq} + Z_{wq}^{wq} + Z_{qq}^{qq} \end{aligned} \quad (2.5 - 21)$$

$$\begin{aligned} K_{Hi} = & K_{\dot{p}}^{\dot{p}} + K_{\dot{r}}^{\dot{r}} + K_{\dot{v}}^{\dot{v}} + K_{rq}^{rq} + K_{pq}^{pq} \\ & + K_{vq}^{vq} + K_{uv}^{uv} + K_{ur}^{ur} + K_{wr}^{wr} \\ & + K_{wv}^{wv} + K_{pw}^{pw} \end{aligned} \quad (2.5 - 22)$$

$$\begin{aligned} M_{Hi} = & M_{\dot{q}}^{\dot{q}} + M_{\dot{u}}^{\dot{u}} + M_{\dot{v}}^{\dot{v}} + M_{rr}^{rr} + M_{vr}^{vr} \\ & + M_{rp}^{rp} + M_{pp}^{pp} + M_{vp}^{vp} + M_{uv}^{uv} \\ & + M_{vw}^{vw} + M_{qw}^{qw} + M_{uu}^{uu} + M_{qu}^{qu} \end{aligned} \quad (2.5 - 23)$$

$$\begin{aligned} N_{Hi} = & N_{\dot{r}}^{\dot{r}} + N_{\dot{p}}^{\dot{p}} + N_{\dot{v}}^{\dot{v}} + N_{qp}^{qp} + N_{vp}^{vp} \\ & + N_{vp}^{vp} + N_{rq}^{rq} + N_{vq}^{vq} + N_{vu}^{vu} \\ & + N_{ru}^{ru} + N_{wv}^{wv} \end{aligned} \quad (2.5 - 24)$$



The equalities given in equations (2.5 - 17 and 18) are based entirely upon potential theory and do not necessarily hold in the presence of circulation and viscous effects. If circulation and viscous effects are neglected, these equalities provide reasonably good estimates of some of the second order coefficients which are not directly amenable to measurement by conventional towing tank techniques.

## II - 5.2 Second Order Terms

The second order terms which are not added mass terms are:

$$\begin{aligned}
 X_{H2} = & X_{u^2} + X_{v^2} + X_{w^2} + X_{p^2} \\
 & + X_{uv} + X_{uw} + X_{up} \\
 & + X_{vw} + X_{vp} + X_{wp}
 \end{aligned} \tag{2.5 - 25}$$

$$\begin{aligned}
 Y_{H2} = & Y_{u^2} + Y_{v^2} + Y_{w^2} + Y_{q^2} \\
 & + Y_{uv} + Y_{uw} + Y_{uq} \\
 & + Y_{vw} + Y_{vq} + Y_{wq}
 \end{aligned} \tag{2.5 - 26}$$

$$\begin{aligned}
 Z_{H2} = & Z_{u^2} + Z_{v^2} + Z_{w^2} + Z_{r^2} \\
 & + Z_{uv} + Z_{uw} + Z_{ur} \\
 & + Z_{vw} + Z_{vr} + Z_{wr}
 \end{aligned} \tag{2.5 - 27}$$

$$K_{H2} = K_{u^2} + K_{p^2} + K_{up} \tag{2.5 - 28}$$

$$H_{H2} = H_{v^2} + H_{q^2} + H_{vq} \tag{2.5 - 29}$$

$$N_{H2} = N_{w^2} + N_{r^2} + N_{wr} \tag{2.5 - 30}$$



The symmetry plane (xz plane) force and moment terms (X, Z, M), which involve products of the symmetry plane velocities (u, w, q) with the out of plane velocities (v, p, r) must be zero for the reason that the same force or moment must result if v, p, r are replaced by -v, -p, -r. This does not hold true with respect to products of xz plane velocities or to products of out of plane velocities.

Another symmetry argument that can be made is that a symmetry plane velocity or products of symmetry plane velocities should not cause out of the plane forces or moments. For example, there should be no Y force resulting from a w velocity or even a combination of w and u velocities.

After removing these symmetry terms from equations (2.5 - 25 through 30) the second order hydrodynamic terms left are:

$$X_{H2} = X_{u^2} u^2 + X_{v^2} v^2 + X_{w^2} w^2 + X_{p^2} p^2 \\ + X_{uw} uw + X_{vp} vp \quad (2.5 - 31)$$

$$Y_{H2} = Y_{v^2} v^2 + Y_{uv} uv + Y_{vw} vw + Y_{vq} vq \quad (2.5 - 32)$$

$$Z_{H2} = Z_{u^2} u^2 + Z_{v^2} v^2 + Z_{w^2} w^2 + Z_{r^2} r^2 \\ + Z_{uw} uw + Z_{vr} vr \quad (2.5 - 33)$$

$$K_{H2} = K_{p^2} p^2 + K_{up} up \quad (2.5 - 34)$$

$$M_{H2} = M_{v^2} v^2 + M_{q^2} q^2 \quad (2.5 - 35)$$

$$N_{H2} = N_{r^2} r^2 + N_{vr} vr \quad (2.5 - 36)$$



## II - 5.3 Linear Terms

The linear terms in the hydrodynamic force equations are:

$$X_{HL} = X_u u + X_v v + X_w w + X_p p + X_q q + X_r r \quad (2.5 - 37)$$

$$Y_{HL} = Y_u u + Y_v v + Y_w w + Y_p p + Y_q q + Y_r r \quad (2.5 - 38)$$

$$Z_{HL} = Z_u u + Z_v v + Z_w w + Z_p p + Z_q q + Z_r r \quad (2.5 - 39)$$

$$K_{HL} = K_u u + K_v v + K_w w + K_p p + K_q q + K_r r \quad (2.5 - 40)$$

$$M_{HL} = M_u u + M_v v + M_w w + M_p p + M_q q + M_r r \quad (2.5 - 41)$$

$$N_{HL} = N_u u + N_v v + N_w w + N_p p + N_q q + N_r r \quad (2.5 - 42)$$

In order to determine which of these terms should be retained, each term must, in general be considered on its own merits. There is, however, one group of terms all of which may be eliminated on the basis of the assumed xz plane of symmetry.

The coefficients which, due to symmetry, must be zero are:

- (1) those that involve derivatives of the symmetry plane forces and moment with respect to the out of plane velocities (v, p, r),
- (2) the out of plane force (Y) and moments (K, N) which would arise from an in the symmetry plane velocity (u, w, q).

Those that fall in the first category are of the type which require the force or moment to stay the same while the velocity can change sign. Those of the second category would require a force perpendicular to the plane of symmetry to result from a flow in the plane of symmetry.





Eliminating these terms from the linear terms equations, results in the following:

$$X_{HL} = X_u + X_w + X_q \quad (2.5 - 43)$$

$$Y_{HL} = Y_v + Y_p + Y_r \quad (2.5 - 44)$$

$$Z_{HL} = Z_u + Z_w + Z_q \quad (2.5 - 45)$$

$$K_{HL} = K_v + K_p + K_r \quad (2.5 - 46)$$

$$M_{HL} = M_u + M_w + M_q \quad (2.5 - 47)$$

$$N_{HL} = N_v + N_p + N_r \quad (2.5 - 48)$$

## II - 5.4 Discussion of Terms

The hydrodynamic force and moment equations that result after eliminating the symmetry terms will now be looked at in order to further reduce the number of terms in the equations.

Of first importance is the decision to retain all terms, or a form from which they can be derived, that are included in "The Standard Equations of Motion for Submarine Simulation" (see ref 8) that would apply to an unpropelled vehicle.

In general, the terms which are retained herein but are not retained by either NSRDC or EIT/IL are done so with the idea that not all submersibles possess the near fore and aft and symmetries that modern military submarines and the DSRV possess.

The procedure to be followed will be to look at the terms that remain after the symmetry terms have been eliminated and the terms retained by other authors have been set aside.



Prior to looking at the individual force and moment equations, the effect of the choice of expansion point for the Taylor series should be investigated.

The most common operating point about which hydrodynamic forces and moments are expanded is some finite forward velocity. When this is done, the linear terms given by equations (2.5 - 43 through 48) exist. These terms include the effect of circulation which does not appear in the potential theory and the Munk moments which arise from the potential theory. Additionally these terms account for the effect that some finite initial velocity has upon the drag terms.

For the present study of emergency ascent trajectories, the initial operating condition is for the vehicle to be at rest in the fluid. Since the force causing the vehicle to ascend is the result of releasing ballast from any position on the vehicle, it is as likely for the vehicle to start moving astern as it is ahead. With this sort of operating condition, the most reasonable expansion point for the Taylor series is then the zero velocity condition. This, however, presents the problem of completely eliminating all the linear terms from the series expansion, since they must be evaluated at the expansion point, zero velocity. For example:

$$w \left[ \frac{\partial x_i}{\partial v^*} \right]_{u = v_0} = 0 \quad \text{since } u_0 = 0$$

Dispite the elimination of the linear terms in the Taylor series expansion, we are dealing with a real fluid and the effect of circulation will still arise as the vehicle commences to move and the potential theory still indicates that the Munk moments exist. The logical place for them to be included is, of course, in the second order terms such as  $M_{uv}$ . Therefore, in the development that follows it must be remembered, that what is



generally included as a linear effect is now part of the second order effects.

The drag effects represented by  $Z_w$ ,  $Z_{vw} w^2$ , etc. in the usual case must now be represented by only the second order terms  $Z_{vw} w^2$ , etc.

In the interest of developing as general a set of equations as possible, the linear terms usually appearing in the hydrodynamic equations shall be retained, though zero for this particular case.



### III - 5.4.1 Axial Force

The axial force equation without symmetry terms is:

$$\begin{aligned}
 X_H = & X_{\dot{u}} + X_{2q^2} + X_{2r^2} + X_{vr} + X_{wq} + X_{pr} \\
 & + X_{2u^2} + X_{2v^2} + X_{2w^2} \\
 & + X_{\dot{w}} + X_{\dot{q}} + X_{uq} + X_{uw} + X_{vp} \\
 & + X_u + X_w + X_q
 \end{aligned}
 \tag{2.5 - 49}$$

where the first two lines represent the terms to be arbitrarily retained. The last two lines contain those terms which require further investigation before being retained or rejected.

The linear term  $X_u$ , will be dropped in favor of the non-linear  $X_{2u^2}$  which equally well represents the drag phenomena. This is especially true if consideration is taken of the non-dimensionalizing parameters involved.  $X_u$  is non-dimensionalized by dividing by  $(\frac{1}{2}\rho l^2 U)$  where  $U$  is, in general, the velocity of the origin of the body axes. Therefore, rather than leave the dimensions of  $X_u$  a function of velocity, we can take a further derivative with respect to  $u$  and eliminate the velocity dependence. This would then give us the alternative non-linear form indicated above.

The linear terms  $X_w$  and  $X_q$  are assumed to be zero on the basis of experimental results. (See table I of ref 2.)

The added mass terms  $X_{\dot{w}}$ ,  $X_{\dot{q}}$  and  $X_{uq}$  are greatly dependent upon the vehicle shape. If there were fore and aft symmetry there would be no axial force resulting from  $X_{\dot{w}}$ . If, however, the vehicle had a form such as ALVIN, which possess no fore and aft symmetry, there may well be forces arising from  $X_{\dot{w}}$ . Very much similar arguments can be said for  $X_{\dot{q}}$  and  $X_{uq}$  and therefore they have been retained in the equations.





The second order term  $X_{uw}$  is assumed to be zero on the basis of experimental results (see table III of ref 2).

The one remaining coefficient  $X_{vp}$  is a second order roll transverse velocity coupling coefficient which appears to be essentially zero.

## II - 5.4.2 Lateral Force

The lateral force equation without symmetry terms is:

$$\begin{aligned}
 Y_H = & Y_{\dot{v}} \dot{v} + Y_{\dot{p}} \dot{p} + Y_{\dot{r}} \dot{r} + Y_{wp} \dot{w} \dot{p} + Y_{wr} \dot{w} \dot{r} + Y_{pq} \dot{p} \dot{q} + Y_{qr} \dot{q} \dot{r} \\
 & + Y_{v^2} v^2 + Y_{vq} v \dot{q} + Y_{vw} v \dot{w} \\
 & + Y_{vv} v + Y_{vp} v \dot{p} + Y_{vr} v \dot{r} \\
 & + Y_{ur} \dot{u} \dot{r} + Y_{up} \dot{u} \dot{p} + Y_{uv} \dot{u} \dot{v}
 \end{aligned} \tag{2.5 - 50}$$

where the first three lines represent the terms to be arbitrarily retained.

On the basis of the potential theory developed in section II - 5.2,  $Y_{up}$  and  $Y_{ur}$  are of the order of magnitude of  $X_w$  and  $X_u$  respectively. Strumpf, in reference (2), retains these terms but notes that there is little or no experimental data available for  $Y_{up}$  while experimental results for  $Y_{ur}$  indicate that it is important.

Similarly,  $Y_{uv}$  is also believed to be of importance on the basis of experimental results cited in reference (2).

## II - 5.4.3 Normal Force

The normal force equation without symmetry terms is:



$$\begin{aligned}
Z_H = & Z_{\dot{w}} + Z_{\dot{q}} + Z_{vp} + Z_{rp} + Z_{pp}^2 \\
& + Z_{vv}^2 + Z_{ww}^2 + Z_{rr}^2 + Z_{vr} \\
& + Z_{\dot{w}} + Z_{\dot{q}} + Z_{\dot{u}} \\
& + Z_{\dot{u}} + Z_{uq} + Z_{wq} + Z_{qq} + Z_{uu}^2 + Z_{uw} \quad (2.5 - 51)
\end{aligned}$$

where the first three lines are the arbitrarily retained terms.

The added mass terms  $Z_{\dot{u}}$ ,  $Z_{uq}$ ,  $Z_{wq}$  and  $Z_{qq}$  are retained on the possibility of a less symmetric vehicle's giving rise to this sort of term. Potential theory estimates  $Z_{uq}$  to be of order  $X_u$ , which is not negligible,  $Z_{\dot{u}}$  and  $Z_{wq}$  to be of order  $X_w$ , which was not neglected previously and  $Z_{qq}$  of order  $X_q$  according to potential theory.

The  $Z_{uu}$  term is shown to be important on the basis of experimental results (see ref 2).

#### II - 5.4.4 Rolling Moment

The rolling moment equation without symmetry terms is:

$$\begin{aligned}
K_H = & K_{\dot{p}} + K_{\dot{r}} + K_{\dot{v}} + K_{rq} + K_{pq} + K_{vq} \\
& + K_{vr} + K_{wv} + K_{wp} + K_{p^2}^2 \\
& + K_v + K_p + K_r \\
& + K_{uv} + K_{ur} + K_{up} \quad (2.5 - 52)
\end{aligned}$$

where the first three lines represent the arbitrarily retained terms.

Here again there is little or no experimental evidence available from which estimates of  $K_{uv}$ ,  $K_{ur}$  and  $K_{up}$  may be made. Potential theory indicates that these terms are small and, therefore, these terms are neglected.



## II - 5.4.5 Pitching Moment

The pitching moment equation without symmetry terms is:

$$\begin{aligned}
 M_H = & M_{\dot{q}} + M_{\dot{w}} + M_{\dot{r}} r^2 + M_{vr} + M_{rp} + M_{pp} p^2 + M_{vp} \\
 & + M_{ww} w^2 + M_{wq} + M_{uu} u^2 \\
 & + M_{vv} v^2 + M_{qq} q^2 + M_w + M_q + M_u \\
 & + M_{\dot{u}} + M_{uw} + M_{uq} \quad (2.5 - 53)
 \end{aligned}$$

where the first three lines contain the arbitrarily retained terms.

Equations (2.5 - 18) show that the added mass term  $M_{\dot{u}}$  is of the same size as  $X_{\dot{u}}$  and  $M_{qw}$  which have been retained. Similarly  $M_{uq}$  is of the same size as  $M_{\dot{u}}$ . Experimental evidence cited by Strumpf supports the retention of  $M_{uq}$ .

The term  $M_{uw}$  is, in accordance with equations (2.5 - 18), equal to  $(X_{\dot{u}} - Z_{\dot{w}})$ . For most vehicles the  $Z_{\dot{w}}$  term is considerably larger than  $X_{\dot{u}}$  and therefore the term  $M_{uw}$  should be retained.

## II - 5.4.6 Yawing Moment

The yawing moment equation without symmetry terms is:

$$\begin{aligned}
 M_H = & N_{\dot{r}} \dot{r} + N_{\dot{p}} \dot{p} + N_{\dot{v}} \dot{v} + N_{pq} p \dot{q} + N_{vp} v \dot{p} + N_{rq} r \dot{q} \\
 & + N_{vv} v v + N_{vq} v \dot{q} + N_{vv} v^2 \\
 & + N_{rr} r^2 + N_{vr} v \dot{r} \\
 & + N_v v + N_p p + N_r r \\
 & + N_{up} u \dot{p} + N_{vu} v \dot{u} + N_{ru} r \dot{u} \quad (2.5 - 54)
 \end{aligned}$$



where the first four lines contain the terms arbitrarily retained.

Equations (2.5 - 18) show that  $N_{vu}$  is equal to  $Y_v - X_u$ ,  $N_{up} = N_{vq}$  and  $N_{ru} = N_v$ . Since  $Y_v$  is of order of magnitude larger than  $X_u$ ,  $N_{vu}$  is of order of magnitude larger than  $X_u$ ,  $N_{vu}$  is of order  $Y_v$  and not negligible.  $N_v$  and  $N_{vq}$  and retained by the other authors and therefore,  $N_{up}$  and  $N_{ru}$  should also be retained in order to be consistent.

## II - 6 Equations of Motion for Free Ascent

The conservation of momentum equations, equations (2.3 - 32 through 37), as derived in section II - 3, the gravity forces, equations (2.4 - 2 through 2.4 - 7) from section II - 4 and the hydrodynamic force equations developed in section II - 5 will now be combined to give the final form for the equations of motion for submersibles in six degrees of freedom with varying mass and center of mass.

Several of the terms retained are not generally found in most developments because the terms are not experimentally or analytically obtained by present methods.

As it is not the purpose of this paper to evaluate additional terms for the equations, these additional terms will be retained but set to zero in the computation of ascent trajectories.

The equations of motion for a vehicle with varying mass will be presented in the following manner: the left hand side of the equation represents the rigid body dynamics, the right hand side represents the hydrodynamic forces and moments acting on the body and causing the motions.

The hydrodynamic terms presented here have been non-dimensionalized in the usual manner as described in reference (6). Typical non-dimensional forms of the hydrodynamic terms are presented in the nomenclature.





For simplicity, the primes have been omitted from the terms in the equations presented.

The equations of motion for a freely ascending vehicle with variable mass are:

#### AXIAL FORCE

$$\begin{aligned}
 m \left[ \dot{u} - rv + qw - x_G (q^2 + r^2) + y_G (pq - \dot{r}) + z_G (pr + \dot{q}) \right] = \\
 \frac{\rho}{2} l^2 (X_{uu} u^2 + X_{vv} v^2 + X_{ww} w^2) \\
 + \frac{\rho}{2} l^3 (X_{\dot{u}} \dot{u} + X_{\dot{w}} \dot{w} + X_{uq} uq + X_{vr} vr + X_{wq} wq) \\
 + \frac{\rho}{2} l^4 (X_{qq} q^2 + X_{rr} r^2 + X_{rp} rp + X_{\dot{q}} \dot{q}) \\
 - (W - B) \sin \theta
 \end{aligned} \tag{2.6 - 1}$$

#### LATERAL FORCE

$$\begin{aligned}
 m \left[ \dot{v} - pw + ru - y_G (r^2 + p^2) + z_G (qr - \dot{p}) + x_G (qp + \dot{r}) \right] = \\
 \frac{\rho}{2} l^2 (Y_{vv} v^2 + Y_{uv} uv + Y_{vu} uv + Y_{vw} vw) \\
 + \frac{\rho}{2} l^3 (Y_{\dot{v}} \dot{v} + Y_{ur} ur + Y_{rur} + Y_{vq} vq) \\
 + \frac{\rho}{2} l^3 (Y_{up} up + Y_p up + Y_{wp} wp + Y_{vr} vr) \\
 + \frac{\rho}{2} l^4 (Y_{\dot{p}} \dot{p} + Y_{\dot{r}} \dot{r} + Y_{pq} pq + Y_{qr} qr) \\
 + (W - B) \sin \phi \cos \theta
 \end{aligned} \tag{2.6 - 2}$$



# NORMAL FORCE

$$\begin{aligned}
 m \left[ \dot{w} - qu + pv - z_G (p^2 + q^2) + x_G (rp - \dot{q}) + y_G (rq + \dot{p}) \right] = \\
 \frac{\rho}{2} l^2 (Z_{uu} \dot{u} + Z_{uu} u^2 + Z_{vv} \dot{v}^2 + Z_{vv} v^2 + Z_{uw} \dot{u} + Z_{uw} u^2) \\
 + \frac{\rho}{2} l^3 (Z_{\dot{u}} \dot{u} + Z_{\dot{w}} \dot{w} + Z_{vp} \dot{v} + Z_{vr} \dot{v} + Z_{uq} \dot{u} + Z_{wq} \dot{w}) \\
 + \frac{\rho}{2} l^4 (Z_{\dot{q}} \dot{q} + Z_{pp} p^2 + Z_{qq} q^2 + Z_{rr} r^2 + Z_{rp} rp) \\
 + (W - B) \cos \theta \cos \phi \quad (2.6 - 3)
 \end{aligned}$$

# ROLLING MOMENT

$$\begin{aligned}
 I_{xx} \dot{p} + I_{xz} (\dot{r} + pq) + (I_{zz} - I_{yy}) q\dot{r} \\
 + m \left[ y_G (\dot{w} + pv - qu) - z_G (\dot{v} + ru - pw) \right] = \\
 \frac{\rho}{2} l^3 (K_{vv} v^2 + K_{uv} \dot{u} + K_{vw} \dot{v}) \\
 + \frac{\rho}{2} l^4 (K_{\dot{v}} \dot{v} + K_{up} \dot{u} + K_{ur} \dot{u} + K_{vq} \dot{v} + K_{wp} \dot{w} + K_{wr} \dot{w}) \\
 + \frac{\rho}{2} l^5 (K_{\dot{p}} \dot{p} + K_{\dot{r}} \dot{r} + K_{pp} p^2 + K_{pq} pq + K_{qr} qr) \\
 + (y_G^W - y_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \cos \theta \sin \phi \quad (2.6 - 4)
 \end{aligned}$$



# PITCHING MOMENT

$$\begin{aligned}
 & I_{yy} \dot{q} + I_{xz} (r^2 + p^2) + (I_{xx} - I_{zz}) rp \\
 & + m \left[ z_G (\dot{u} + qw - rv) - x_G (\dot{w} + pv - qu) \right] = \\
 & \frac{\rho}{2} l^3 (M_{uu} u^2 + M_u u^2 + M_{vv} v^2 + M_{vw} w^2 + M_{uw} uv + M_w ur) \\
 & + \frac{\rho}{2} l^4 (M_u \dot{u} + M_w \dot{w} + M_{vp} vp + M_{vr} vr + M_{wq} wq) \\
 & + \frac{\rho}{2} l^4 (M_q uq + M_{uq} uq) \\
 & + \frac{\rho}{2} l^5 (M_q \dot{q} + M_{pp} p^2 + M_{qq} q^2 + M_{rr} r^2 + M_{rp} rp) \\
 & - (x_G^W - x_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \sin \theta \quad (2.6 - 5)
 \end{aligned}$$

# YAWING MOMENT

$$\begin{aligned}
 & I_{zz} \dot{r} + I_{xz} (\dot{p} + rq) + (I_{yy} - I_{xx}) pq \\
 & + m \left[ x_G (\dot{v} + ru - pw) - y_G (\dot{u} + qw - rv) \right] = \\
 & \frac{\rho}{2} l^3 (N_{vv} v^2 + N_v uv + N_{uv} uv + N_{vw} vw) \\
 & + \frac{\rho}{2} l^4 (N_v \dot{v} + N_{wr} wr + N_{wp} wp + N_{ur} ur + N_{ur} ur) \\
 & + \frac{\rho}{2} l^4 (N_{up} up + N_p up + N_{vq} vq) \\
 & + \frac{\rho}{2} l^5 (N_p \dot{p} + N_r \dot{r} + N_{rr} r^2 + N_{pq} pq + N_{qr} qr) \\
 & + (x_G^W - x_B^B) \cos \theta \sin \phi + (y_G^W - y_B^B) \sin \theta \quad (2.6 - 6)
 \end{aligned}$$



### II - 7 Summary

The axis systems to be used in the problem are discussed and the transformations from the earth fixed to the body fixed axes are developed.

A derivation of the dynamical equations for a vehicle with a varying mass and center of mass is then made using a Lagrangian formalism. An assumption that the reduction in mass due to releasing ballast can be represented as a quasi-steady process is discussed.

The forces acting on the body are then developed by expanding a functional representation of the forces in a Taylor series. The terms in the series are then discussed.

The equations are then non-dimensionalized for final presentation.





## CHAPTER III

### SOLUTION OF THE EQUATIONS OF MOTION

In the previous chapter a system of equations of motion were developed for which a solution must be found in order to obtain the ascent trajectory of a vehicle. It is possible that an analytic solution to this set of simultaneous non-linear differential equations could be found, however, it is much more practical to assume that a stepwise linear approximation to these equations. This approach has been used in many simulation studies of which the DSRV control system simulation (see ref 5) and determining the effect of hull shape non-linearities (see ref 4) are just two.

The equations as developed in Chapter II conform to the notation used by Strumpf (see ref 2) which does not conform with either the hydrodynamic terms format used by the MIT Instrumentation Laboratory for the DSRV control system studies and simulation (see ref 5), or the standard equations of motion for submarine simulation as used by NSRDC (see ref 8). In order that available hydrodynamic coefficients be utilized, the notation of Chapter II will be modified in this chapter to conform with that of the NSRDC equations. The choice of the NSRDC form over the MIT/IL form was made for the reason that it is more likely that vehicle coefficients will be obtained from NSRDC than from MIT/IL which must also get its data from other sources. The MIT/IL notation does possess the advantage of having the dimensional forms of the coefficients independent of velocity.

Before a stepwise solution to the equations can be obtained, the equations must be put into a form which is amenable to this technique.



### III - 1 Revised Equations of Motion

The vehicle equations of motion are generally expressed in the form:

$$n \frac{d\vec{V}}{dt} = - n \left( \frac{d\vec{I}}{dt} \times \vec{EG} + \vec{W} \times (\vec{V} + \vec{W} \times \vec{EG}) \right) + \vec{F}_{HYD} + \vec{F}_{EFF} \quad (3.1 - 1)$$

$$\vec{I} \frac{d\vec{W}}{dt} = - \vec{W} \times \vec{I}\vec{W} - m\vec{EG} \times \left( \frac{d\vec{V}}{dt} + \vec{W} \times \vec{V} \right) + \vec{M}_{HYD} + \vec{M}_{EFF} \quad (3.1 - 2)$$

where  $\frac{d\vec{V}}{dt} = \dot{u}, \dot{v}, \dot{w}$ ,  $\frac{d\vec{W}}{dt} = \dot{p}, \dot{q}, \dot{r}$  and  $\vec{I}$  is the inertial tensor.

To determine ascent trajectories in a stepwise linear fashion on a digital computer it is useful to rearrange the above equations so that all the derivatives are on the left side of the equations. The resulting equations are of the form:

$$\frac{d\vec{V}'}{dt} = - m\vec{W} \times (\vec{V} + \vec{W} \times \vec{EG}) + \vec{F}_{HYD} + \vec{F}_{EFF} \quad (3.1 - 3)$$

$$\frac{d\vec{W}'}{dt} = - \vec{W} \times \vec{I}\vec{W} - m\vec{EG} \times (\vec{W} \times \vec{V}) + \vec{EG} \times \vec{W}_V + \vec{M}_{HYD} + \vec{M}_{EFF} \quad (3.1 - 4)$$

where

$$\begin{bmatrix} \frac{d\vec{V}'}{dt} \\ \frac{d\vec{W}'}{dt} \end{bmatrix} = [\mathbf{M}] \begin{bmatrix} \frac{d\vec{V}}{dt} \\ \frac{d\vec{W}}{dt} \end{bmatrix} \quad (3.1 - 5)$$

and  $[\mathbf{M}]$  is the six by six derivative coefficient matrix given on page 48.



$m - X_u$	0	$X_w$	0	$mz_G - X_q$	$-my_G$
0	$m - Y_v$	0	$-mz_G - Y_p$	0	$mz_G - Y_r$
$Z_u$	0	$m - Z_w$	$my_G$	$-mz_G - Z_q$	0
0	$-mz_G - X_v$	$my_G$	$I_{ux} - X_p$	0	$I_{xz} - X_r$
$mz_G - X_u$	0	$-mz_G - Z_w$	0	$I_{yy} - M_q$	0
$-my_G$	$mz_G - N_v$	0	$I_{xz} - N_p$	0	$I_{zz} - N_r$

Derivative Coefficient Matrix



The actual derivatives  $\frac{dV}{dt}$  and  $\frac{dM}{dt}$  are obtained from:

$$\begin{bmatrix} \frac{dV}{dt} \\ \frac{dM}{dt} \end{bmatrix} = [M]^{-1} \begin{bmatrix} \frac{dV'}{dt} \\ \frac{dM'}{dt} \end{bmatrix} \quad (3.1 - 6)$$

where  $[M]^{-1}$  is the inverse of  $[M]$ .

The equations to be solved for  $\frac{dV'}{dt}$  and  $\frac{dM'}{dt}$  are then given by the following:

$$\begin{aligned} \frac{dV'}{dt} = & -m \left[ -rv + qw - x_G (q^2 + r^2) + y_G pq + z_G pr \right] \\ & + \frac{\rho}{2} l^2 (X_{uu} u^2 + X_{vv} v^2 + X_{ww} w^2) \\ & + \frac{\rho}{2} l^3 (X_{uq} uq + X_{vr} vr + X_{wq} wq) \\ & + \frac{\rho}{2} l^4 (X_{qq} q^2 + X_{rr} r^2 + X_{rp} rp) \\ & - (W - B) \sin \theta + X_{EFF} \end{aligned} \quad (3.1 - 7)$$

$$\begin{aligned} \frac{dV'}{dt} = & -m \left[ -pw + ru - y_G (r^2 + p^2) + z_G qr + x_G qp \right] \\ & + \frac{\rho}{2} l^2 (Y_{v|v|} v | (v^2 + w^2)^{\frac{1}{2}} | + Y_{uv} uv + Y_{vw} vw + Y_{*} u^2) \\ & + \frac{\rho}{2} l^3 (Y_{p} up + Y_{r} ur + Y_{vq} vq + Y_{vp} vp + Y_{wr} wr) \\ & + \frac{\rho}{2} l^3 (Y_{v|r|} \frac{v}{|r|} | (v^2 + w^2)^{\frac{1}{2}} | | r |) \\ & + \frac{\rho}{2} l^4 (Y_{pq} pq + Y_{qr} qr) + (W - B) \sin \phi \cos \theta + Y_{EFF} \end{aligned} \quad (3.1 - 8)$$





$$\begin{aligned}
\frac{dw'}{dt} = & -m \left[ -qu + pv - z_G (p^2 + q^2) + x_G rp + y_G rq \right] \\
& + \frac{\rho}{2} l^2 (z_{uu} + z_{vv} v^2 + z_{w|w|} w | (v^2 + w^2)^{\frac{1}{2}} | + z_{vw} uv) \\
& + \frac{\rho}{2} l^2 (z_{|w|} u|w| + z_{ww} w | (v^2 + w^2)^{\frac{1}{2}} |) \\
& + \frac{\rho}{2} l^3 (z_{vp} vp + z_{vr} vr + z_{q|q|} \frac{w}{|w|} | (v^2 + w^2)^{\frac{1}{2}} | |q|) \\
& + \frac{\rho}{2} l^4 (z_{pp} p^2 + z_{qq} q^2 + z_{rr} r^2 + z_{rp} rp) \\
& + (W - B) \cos \theta \cos \phi + Z_{EFF}
\end{aligned} \tag{3.1 - 9}$$

$$\begin{aligned}
\frac{dp'}{dt} = & -I_{xz} pq + (I_{yy} - I_{zz}) qr - m \left[ -z_G (-pw + rq) + y_G (pv - qu) \right] \\
& + \frac{\rho}{2} l^3 (K_{v|v|} v | (v^2 + w^2)^{\frac{1}{2}} | + K_{uv} uv + K_{vw} vw + K_v u^2) \\
& + \frac{\rho}{2} l^4 (K_{p|p|} p | p | + K_{ur} ur + K_{vq} vq + K_{wp} wp + K_{vr} vr) \\
& + \frac{\rho}{2} l^5 (K_{p|p|} p | p | + K_{pq} pq + K_{qr} qr) \\
& + (y_G^W - y_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \cos \theta \sin \phi + K_{EFF}
\end{aligned} \tag{3.1 - 10}$$



$$\begin{aligned}
\frac{dq}{dt} = & -I_{xz} (r^2 - p^2) + (I_{zz} - I_{xx}) rp \\
& - m \left[ -x_G (-qu + pv) + z_G (qw - rv) \right] \\
& + \frac{\rho}{2} l^3 (M_u u^2 + M_{vv} v^2 + M_{|w|w} |(v^2 + w^2)^{\frac{1}{2}}| + M_{vw}) \\
& + \frac{\rho}{2} l^3 (M_{|w|w} (v^2 + w^2)^{\frac{1}{2}}| + M_{|w|} u|w|) \\
& + \frac{\rho}{2} l^4 (M_{vp} vp + M_{vr} vr + M_{uq} uq + M_{|w|q} |(v^2 + w^2)^{\frac{1}{2}}| q) \\
& + \frac{\rho}{2} l^5 (M_{pp} p^2 + M_{q|q|} q|q| + M_{rr} r^2 + M_{rp} rp) \\
& - (x_G^W - x_B^B) \cos \theta \cos \phi - (z_G^W - z_B^B) \sin \theta + M_{EFF}
\end{aligned} \tag{3.1 - 11}$$

$$\begin{aligned}
\frac{dr}{dt} = & -I_{zx} rq + (I_{xx} - I_{yy}) pq - m \left[ -y_G (-rv + qw) + z_G (ru - pw) \right] \\
& + \frac{\rho}{2} l^3 (N_{|v|v} v |(v^2 + w^2)^{\frac{1}{2}}| + N_{vw} vw + N_{uv} uv + N_u u^2) \\
& + \frac{\rho}{2} l^4 (N_{vr} vr + N_{vp} vp + N_{vq} vq) \\
& + \frac{\rho}{2} l^4 (N_{ur} ur + N_{|v|r} |(v^2 + w^2)^{\frac{1}{2}}| r + N_{pup}) \\
& + \frac{\rho}{2} l^5 (N_{r|r} r|r| + N_{pq} pq + N_{qr} qr) \\
& + (x_G^W - x_B^B) \cos \theta \sin \phi + (y_G^W - y_B^B) \sin \theta + N_{EFF}
\end{aligned} \tag{3.1 - 12}$$

In these equations, unlike equations (2.6 - 1 through 7) from

which they come, the linear terms  $Y_v, Y_p, Y_r, Z_u, Z_v, M_u, M_v, M_q, N_v, N_p$  and  $N_r$  are combined with the non-linear terms  $Y_{uv}, Y_{up}, Y_{ur}, Z_{uu}, Z_{uv}, M_{uu}, M_{uv}, M_{uq}, N_{uv}, N_{up}, N_{ur}$ . This is done for the reason that these terms are



inseparable from a model test data reduction viewpoint. The terms  $Z_{|w|}$ ,  $Z_{|w|}$ ,  $M_{|w|}$  and  $n_{|w|}$  have been added so as to include all of the NSRDC coefficients. The terms  $X_{EFF}$ ,  $Y_{EFF}$ ,  $Z_{EFF}$ ,  $K_{EFF}$ ,  $M_{EFF}$  and  $N_{EFF}$  have been included in order to allow for the possibility of there being some small effector forces on the vehicle. This inclusion in no way affects the legitimacy of the equations so long as the force does not cause the predominance of one velocity component.

With the equations in this form, a stepwise linear solution can be developed which will be capable of being programmed for use on a high speed digital computer.

### III - 2 Stepwise Linear Solution

A stepwise linear solution is one in which the accelerations are taken as constant over a given time interval. The accelerations that exist over a time interval are determined from the velocities that existed at the end of the previous time interval and the total weight removed from the vehicle. Thus, the right hand side of equations (3.1 - 3 and 3.1 - 4) can be determined at the beginning of each time step. The inertia terms in  $[M]$  must also be recomputed before each step since the mass is changing in a stepwise linear fashion as described in section II - 3. With the foregoing information equation (3.1 - 6) can be solved for the body axes accelerations.

The velocity of the vehicle in the body axis system may then be found by:

$$\begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix}_t = \int_t^t \begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix}_t dt \quad (3.2 - 1)$$



where  $t_0$  is the time at which the ascent started and  $t$  is the present time. The integral may, however, be represented as a sum of integrals over each step in the stepwise solution. Thus:

$$\begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix}_{t_n} = \sum_{n=1}^N \int_{t_{n-1}}^{t_n} \begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix} dt \quad (3.2 - 2)$$

where  $t_{n-1}$  and  $t_n$  are respectively the times at the beginning and end of the interval. The solution has been specified as stepwise linear and the accelerations are to be obtained as constants for the duration of an interval, therefore, the accelerations can be removed from the integral leaving only the trivial integration of  $dt$  from  $t_{n-1}$  to  $t_n$ . Defining  $\Delta t$  as  $t_n - t_{n-1}$ , equation (3.2 - 2) becomes:

$$\begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix}_{t_n} = \sum_{n=1}^N \begin{bmatrix} \vec{V} \\ \vec{W} \end{bmatrix}_{t_{n-1}} \Delta t \quad (3.2 - 3)$$

which gives the translational and rotational velocities of the vehicle in the body axis system.

In order to obtain the actual position of the vehicle relative to its inertial starting point the velocities obtained above must be transformed into the inertial axis system by use of the inverse of the transformation matrixes developed in section 11 - 2.3. The velocities  $\dot{x}$ ,  $\dot{y}$ ,  $\dot{z}$ ,  $\dot{\phi}$ ,  $\dot{\theta}$ ,  $\dot{\psi}$  are obtained from:





$$\begin{bmatrix} \dot{x}_E \\ \dot{y}_E \\ \dot{z}_E \end{bmatrix} = T_B^{-1} \begin{bmatrix} u \\ v \\ w \end{bmatrix}; \quad \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = A^{-1} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (3.2 - 4);$$

$$(3.2 - 5)$$

The position and orientation in the inertial axis system is then determined by integrating the respective velocities from  $t_0$  to  $t$ . Here again the solution is stepwise and may be represented as a sum of the individual steps. In this case, however, the integrand  $\dot{x}_E$ ,  $\dot{y}_E$ , etc. is not a constant. It is, instead, a linear function of time since the acceleration from whence it came is a constant. Therefore the equation describing the vehicle trajectory and orientation becomes:

$$\begin{bmatrix} \vec{x}_E \\ \vec{\phi} \end{bmatrix}_t = \sum_{n=1}^N \frac{1}{2} \left( \begin{bmatrix} \frac{\dot{\vec{x}}_E}{\dot{\phi}} \end{bmatrix}_{t_{n-1}} + \begin{bmatrix} \frac{\dot{\vec{x}}_E}{\dot{\phi}} \end{bmatrix}_{t_n} \right) \Delta t \quad (3.2 - 6)$$

where  $\vec{x}_E = (x_E, y_E, z_E)$  and  $\vec{\phi} = (\phi, \theta, \psi)$ .

The computation of  $\vec{x}_E$  and  $\vec{\phi}$  are the final computations of the step. The procedure is then repeated until some maximum time is reached or some predefined position is reached.

In order to verify the result obtained by the foregoing procedure, and independent trajectory determination must be made.

### III - 3 One Dimensional Ascent Trajectory

Now that a three dimensional second order method of determining free ascent trajectories has been obtained, some check on the results of this procedure is in order. The most logical approach is to reduce the problem to one in the vertical plane only and thereby reducing the complexity of the problem. If a derivation of the equations of motion were



made at this point the resulting equations would be no different from those previously obtained except that some of the coefficients would now be zero. In addition, the solution of the two dimensional equations for a complete trajectory would require the aid of a high speed digital computer.

To avoid the necessity of employing a computer, a simplified method described by Giddings and Louis in reference (9) will be used. This method, as applied to the problem under consideration, reduces to a one dimensional solution of the equations of motion for a vehicle with varying mass.

The one dimensional solution determines the vertical position, velocity and acceleration of the vehicle during its ascent. This information provides a sufficient check of the results of the computer solution of the equations of motion developed in Chapter II. A description of the one dimensional solution follows.

Defining:

$B$  - the net buoyant force

$b$  - the time rate of change of  $B$

$F$  - the sum of all forces in the vertical direction

$g$  - the acceleration due to gravity

$k$  - the virtual mass coefficient

$m'$  - the mass of the vehicle plus the virtual mass

$W$  - the instantaneous vehicle weight.

$z, \dot{z}, \ddot{z}$  - the vertical displacement, velocity and acceleration respectively

$Z_{vw}, Z_w$  - the crossflow drag and added mass coefficients respectively

Newton's laws of motion can be expressed as:



$$F = m' \ddot{z} \quad (3.3 - 1)$$

The force  $F$  is made up of the weight of the jettisoned ballast,  $B$ , plus or minus the hull drag,  $D$ , depending on the direction of motion.

The force due to the jettisoning of ballast is given by:

$$B = \int_0^t b(t) dt \quad (3.3 - 2)$$

Letting the integral be represented by a series of finite steps the buoyant force becomes:

$$B = \sum_{n=1}^N b_n \quad (3.3 - 3)$$

where the  $b_n$  are a sequence of finite weights to be jettisoned and  $n$  is the number of intervals elapsed since time zero.

The force due to hull drag is represented by:

$$D = \frac{1}{2} \rho l^2 \underset{WW}{Z} \dot{z} |\dot{z}| \quad (3.3 - 4)$$

The mass,  $m'$ , of the vehicle can be written as:

$$m' = \frac{W}{g} k \quad (3.3 - 5)$$

$$\text{where } k = \left[ \underset{W}{Z} \left( \frac{1}{2} \rho l^3 \right) / (W/g) \right] + 1 \quad (3.3 - 6)$$

Substituting these expressions into equation (3.3 - 1) the equation of motion becomes:



$$\left( Z_{\frac{1}{2}} \left( \frac{1}{2} \rho l^3 \right) + \frac{W}{g} \right) \ddot{Z} - Z_{\frac{1}{2}} \left( \frac{1}{2} \rho l^2 \right) \ddot{\theta} \left| \dot{Z} \right| - \sum_{n=1}^N b_n = 0 \quad (3.3 - 7)$$

The technique of step by step integration similar to that used in section III - 2 may now be applied to this equation in order to obtain the one dimensional trajectory.

### III - 4 Summary

The notation and terms format to be used in the computer simulation is discussed. The notation used in the equations of motion is modified to conform with that of NSRDC and the equations are rearranged for digital computer solution.

A solution method is developed utilizing a stepwise linear technique. It accepts the vehicle velocities, position, orientation and buoyancy as initial conditions and using equations (3.1 - 6 through 3.1 - 12) it computes the accelerations, velocities, and displacements of the vehicle after a time interval  $\Delta t$ . Before each step the weight, CG, mass and moments of inertia are adjusted.

Finally a simplified one dimensional method is devised for comparison with the computer results.





## CHAPTER IV

### RESULTS AND CONCLUSIONS

In Chapter III the equations of motion were derived for a freely ascending vehicle with varying mass and center of mass. A stepwise linear solution suitable for programming on a digital computer was developed in Chapter III, and the actual program is presented in Appendix A. An equation for a one dimensional ascent trajectory was also developed in Chapter III to provide a check for the three dimensional, six degree of freedom, ascent trajectories program. A program to solve this non-linear differential equation is presented in Appendix D.

In this chapter, the computer simulations and results of these simulations are discussed, conclusions drawn and recommendations for future work in this area made.

#### IV - 1 Results of Computer Simulations

Computer simulations of the ascent trajectories for a vehicle similar to the Deep Submergence Rescue Vehicle were conducted using the IBM 360 computer of the MIT Information Processing Center. These simulations were conducted primarily for the purpose of debugging the ascent trajectories program and determining its operating characteristics and secondarily to study the motion tendencies of the DSRV.

##### IV - 1.1 Program Operating Characteristics

The ascent trajectories program in calculating the vehicle trajectories depends upon the assumed time increment for its accuracy. In general, the time increment assumed can be classed as either too large, too small or all right. Note that the latter category was "all right" not "just right".



The matter of just the right increment requires a discussion of the factors influencing the situation and, therefore, the former categories will be dealt with first.

Should the time increment chosen be too large, the forces acting on the vehicle will not be damped in a natural fashion. A vehicle under the influence of a steady force will continue to accelerate until this force is overcome by another force, and the computer does not see another force until the present time increment ends and the forces resulting from the present motion can be calculated. If the time increment is too long, the motions calculated by the computer become excessive. The eventual result is that the computer run is prematurely terminated. The actual cause of termination can be either program caused or machine caused.

A run is terminated by the program if either the time limit or the depth limit is exceeded. Since reaching the time limit or reaching the depth limit in a natural fashion do not constitute being premature, they are not considered here. The depth limit can, however, be reached in an unnatural fashion as is indicated in Appendix C, section C - 3.

A run is terminated by the computer if the number of extreme value calculations becomes excessive.

Termination for the latter cause occurs before the normal output can be made and, therefore, the only printed output received will be the initial condition printout. Termination for the former cause results in all normal output being printed.

When the time increment assumed is too small the computer round off error dominates the actual calculations and the output is meaningless.

This then leaves us with the category of the time increment being "all right". Factors which effect or are effected by the time increment in



clude ballast removal rate, vehicular velocities and accelerations, and vehicular stability both static and dynamic.

The ballast release rate in pounds per second (real time) can be assumed to be fixed for a given vehicle since, in emergency conditions, all ballast will, in general, be released at as high a rate as possible. Even if this is not done the ballast release rate would normally be specified and not left to the needs of the simulation. Further, the program in no way affects the ballast release rate.

The velocities and accelerations, on the other hand are directly affected by the time increment used. The change in velocity is determined by assuming that the acceleration is constant over the time period and is, therefore, equal to the product of the time increment and the acceleration. The acceleration existing during a time increment is dependent upon the forces acting on the body during that increment. The hydrodynamic forces are, in turn, dependent upon the velocities computed during the previous increment. This interdependence of forces, accelerations and velocities can be the cause of premature termination if the time increment is too large. For instance, a large increment would cause the acceleration to act for too long causing the velocity to be excessive, which in turn would cause the forces in the next increment to be excessive, etc....

The static stability of the vehicle is dependent only upon the shift of the CG relative to the CB, and is, therefore, a function of the ballast release rate only. The dynamic stability is, however, dependant upon the vehicular velocities and accelerations as well as the change in mass caused by the reduction in weight.

The essence of this discussion is that, the time increment to be used for a vehicle in free ascent will be dictated by a combination of the



ballast release rate and the expected accelerations. The ballast release rate will indicate the order of magnitude and the accelerations will refine the increment.

With the proper time increments chosen trajectories can be computed for a variety of initial conditions.

#### IV - 1.2 DSRV Motion Tendencies

The ascent trajectories generated by the ascent program are not those that would be followed by the DSRV, since the coefficients used in the program come from DSRV model tests with the propeller running. They do, however, provide an indication of the ascent trajectories and motion tendencies of that vehicle. Simulations were made with the body axes initially coincident with the inertial axes and with an initial roll angle imposed.

The results of the simulations with the body axes initially coincident with the inertial axes clearly indicate the coupling of pitch and surge which bring about the trajectories of Figure IV.1. This motion becomes even more clear in the velocity plots of Figure IV.2. A tendency toward a negative pitch angle when dumping both trim tanks into the reservoir is also demonstrated.

The simulations involving an initial roll angle indicate the small amount of roll damping and static stability associated with this vehicle. They also indicate a slight side force roll coupling as is evidenced in the printout in Appendix C, section C - 2. The lack of stability also manifested itself by causing the program to terminate prematurely when using a time increment that proved successful for the zero roll case. Eventually an increment of one tenth that used without roll proved successful.





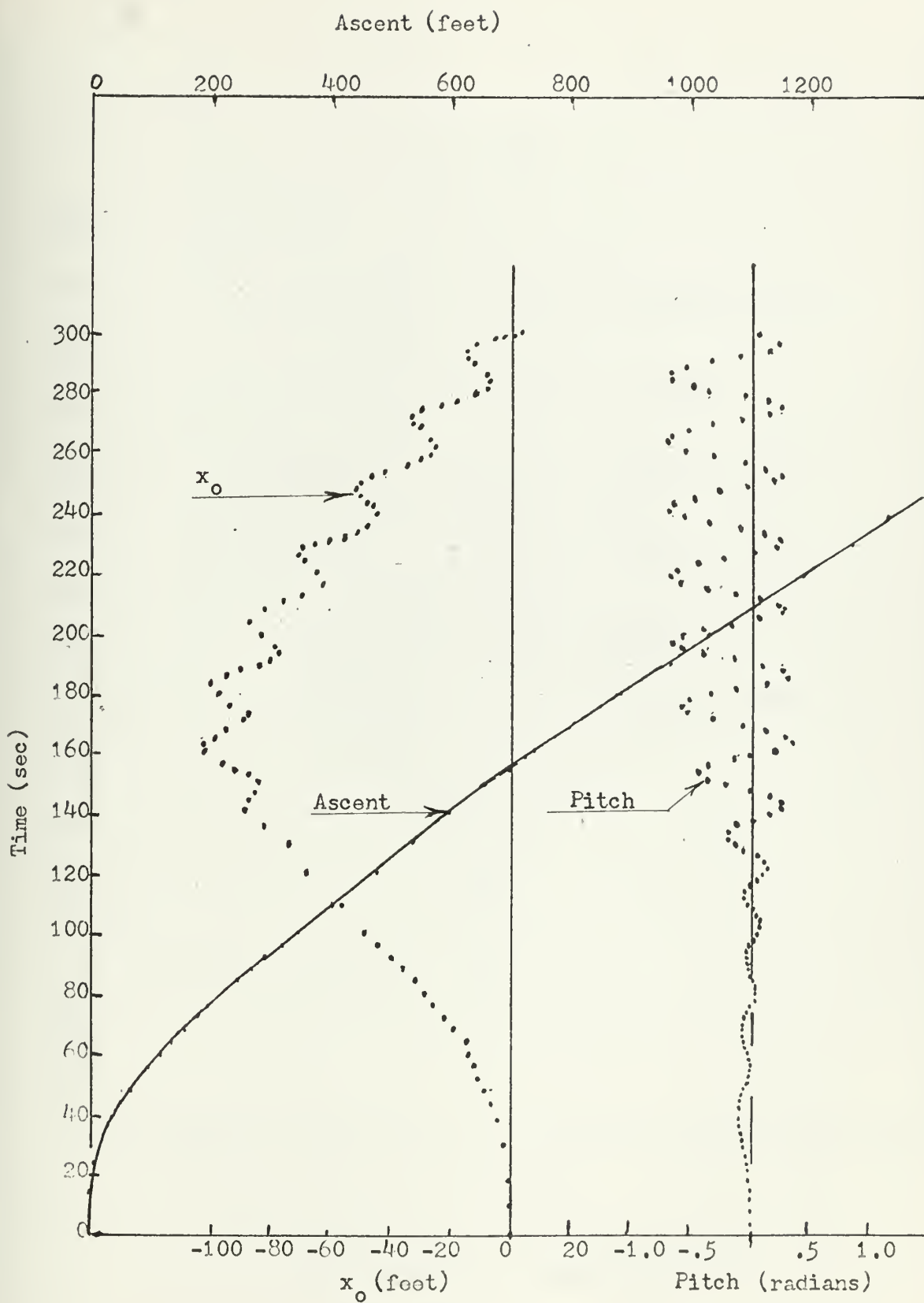


Figure IV.1



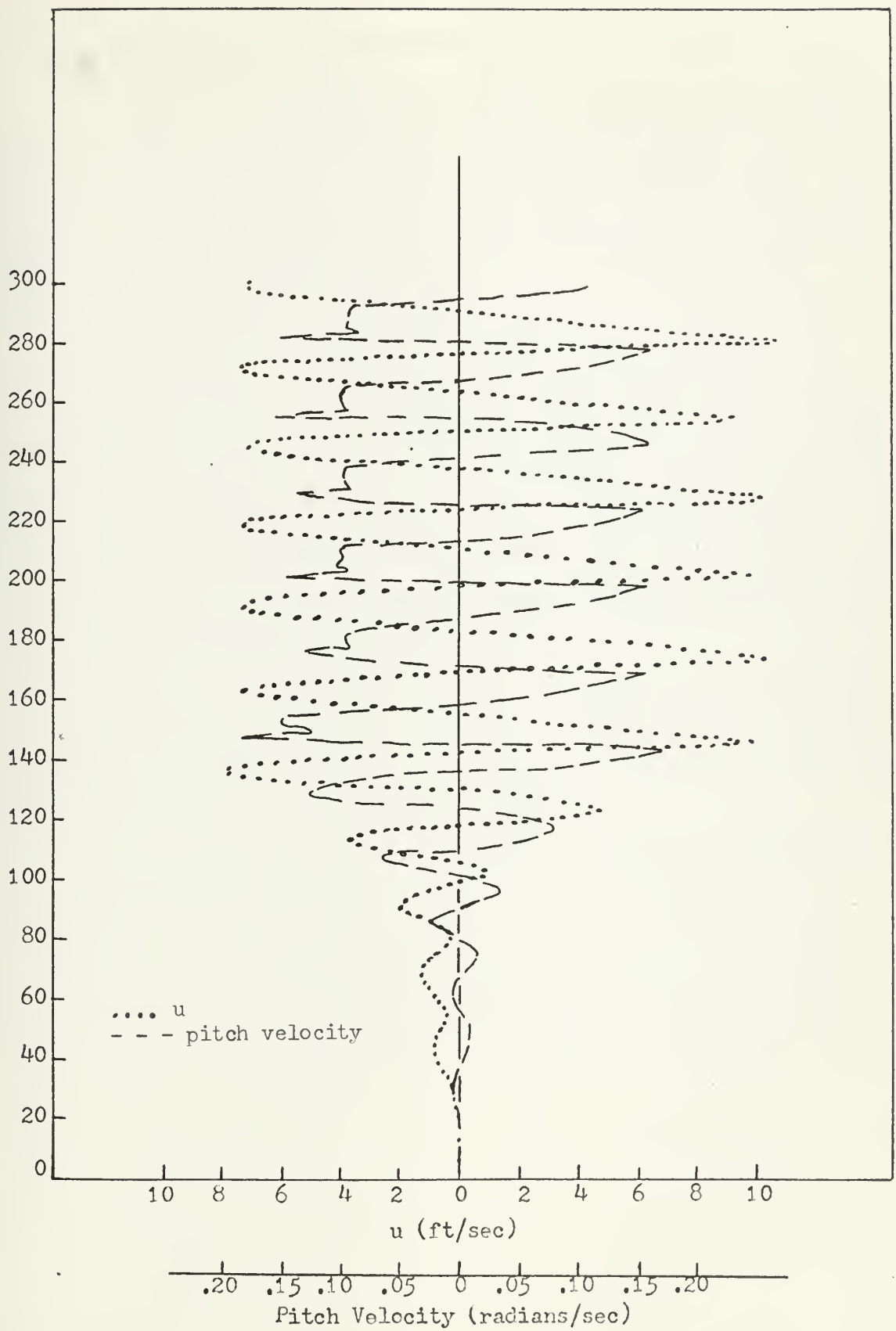


Figure IV.1



#### IV - 2 Conclusions and Recommendations

The computer simulations using the DSRV characteristics have demonstrated the worth of this program in determining the motions of a vehicle as it ascends under the influence of buoyancy alone. They have shown that a vehicle such as the DSRV is quite sensitive to roll without the stabilizing effect of a relatively large forward velocity.

The velocities achieved by the vehicle during ascent indicate that there is a predominant velocity component about which we could expand a Taylor series once the initial acceleration phase of the ascent has been passed. The most likely time for a shift to this sort of formulation is twenty seconds after deballasting has been completed. At that time the vehicle appears to have reached a terminal condition in which the surge and pitch vary between essentially constant limits.

The simulations have indicated that a vehicle with near perfect port and starboard symmetry requires no more than two dimensional equations of motion when there are no side forces present.

It is recommended that future studies be made using coefficients obtained from model tests conducted without propellers running. Also, in view of the slow ascent velocities, it may prove worthwhile to rewrite the equations to include the effects of an ascent propulsor which may prove necessary in order to get a more rapid ascent in other than emergency situations.



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## APPENDIX A

### COMPUTER PROGRAM FOR ASCENT TRAJECTORIES

#### A - 1 General:

The computer program to calculate free ascent trajectories is written for the IBM 360 - 65 digital computer of the MIT Information Processing Center. The program is written in FORTRAN IV (see ref 11 and 12). The program makes use of the matrix manipulation subroutines contained in version III of the IBM "Scientific Subroutine Package" (ref 13) and the mathematical functions contained in the standard "Library Subroutines" (ref 14).

The system subroutines required are:

#### Library Subroutines;

SIN - computes the sine of an angle

COS - computes the cosine of an angle

TAN - computes the tangent of an angle

SQRT - computes the square root of a number

ABS - computes the absolute value of a number

#### Scientific Subroutines;

GMPRD - computes the product of two matrices

MINV - computes the inverse of a matrix

Extensive use is made of the NAMELIST feature of FORTRAN IV for input and output.

The program is divided into seven parts: the MAIN program and six SUBROUTINES.



#### A - 1.1 MAIN Program

The MAIN program acts as an executive reading in initial conditions, vehicle parameters and program control parameters, calling the various subroutines needed to solve the equations of motion and writing out the results of the computations.

The data read in is contained in five NAMELISTS, INCOND, FLUID, VLAITS, VEHICLE and CONTROL, and one controlled format statement. The output is again in accordance with the NAMELISTS plus a single large array, POSIT, containing all the computed results for the entire test period.

Part of the output from MAIN is a set of punched cards which contain all the parameters from NAMELIST INCOND. This output can be used as input data for another run in order to continue the same trajectory if it is desired. A maximum of five hundred steps is allowed in one run.

#### A - 1.2 Subroutine COEFF

COEFF reads in the non-dimensional coefficients and immediately prints them for output. The subroutines then computes dimensionalizing factors, dimensionalizes the coefficients for use in the motion equations and prints the dimensionalized coefficients for output.

The coefficients are read in and printed using the NAMELIST COEFFS.

The dimensionless coefficients are replaced in storage by their dimensional form.

#### A - 1.3 Subroutine BALAST

BALAST computes the changes in weight, mass, center of gravity, and moments of inertia due to the dropping of ballast.

This subroutine is only called during the initial phase of the



trajectory when deballasting takes place.

BALAST calls subroutine AMATRIX since the matrix generated in AMATRIX varies only during the deballasting phase of the ascent.

A maximum of twenty locations for ballast weights is allowed.

There is no printed output from BALAST.

#### A - 1.4 Subroutine AMATRIX

AMATRIX computes the six by six matrix of acceleration term coefficients,  $AM$ , and then inverts the array for use in the solution of the equations of motion.

#### A - 1.5 Subroutine HYDRO

HYDRO computes the hydrodynamic forcing terms and the gravity forcing terms and then sums them, plus any effector forces, to get the total forcing terms for the equations of motion.

HYDRO uses the velocities and angles resulting from the previous steps in order to compute the hydrodynamic and gravity force components acting on the vehicle during the present step.

There is no printed output from HYDRO.

#### A - 1.6 Subroutine TRAJEC

TRAJEC computes the translational and rotational velocities of the vehicle in both body fixed and earth fixed axis systems. In order to do this, TRAJEC also computes the translational and angular velocity transformation matrices  $AINV$  and  $TINV$ .

If the pitch angle becomes ninety degrees the transformation matrix,  $AINV$ , will blow up (mathematically speaking). At this time, the program will print a message saying that this has occurred. At the same time, the computer system will issue a "IBM interrupt, Divide check" message





during computation of the two elements in  $ALW$  which involve division by the cosine of the pitch angle. At this point the system will take the standard corrective action of assigning the value of  $10^{-69}$  to each of these elements.

#### A - 1.7 Subroutines POSITN

POSITN computes the time elapsed and the position of the vehicle relative to the earth fixed origin. The vehicle position includes both translation and rotation. POSITN also stores all the trajectory generation information in the array POSIT for the final output sequence.

There is no printed output from POSITN.

#### A - 2 Input-Output

The variables and constants needed as input for this computer program are read into the program by seven read statements. Table 1 lists all the input variables and the formats under which they are read.

A single computer run must be made to simulate each vehicle. If, however, a run terminates before the vehicle reaches the surface, the punched output from the program gives the input necessary to continue the trajectory on the next run.

The program output gives a time history of the simulation. This data is stored in an array during execution and printed at the end of the run by the main program. During program execution NAMELIST/INCCID/ is printed at the completion of each step. This is done to aid the user in locating the source of any premature program termination. Premature termination is generally caused by incorrect input data.

The dimensions of the storage array restricts the program to 500 time intervals, however, the program storage requirements are such that this dimension can safely be increased to 1000. This, coupled with the



ability to continue a trajectory from one run to the next, allows an unlimited number of intervals during a trajectory.

For sample output see Appendix C.



TABLE 1

## INPUT TO ASCENT PROGRAM

Columns	Format	Symbol	Description
2 - 8		\$INCOND	This namelist will take more than one card and includes the variables described in Table 2. The list begins with \$INCOND and ends with \$END.
2 - 7		\$FLUID	This namelist will take one card and includes the variables described in Table 2.
2 - 8		\$VIBITS	This namelist will take one card and includes the variables described in Table 2.
2 - 8		\$VEHICL	This namelist will take one card and includes the variables described in Table 2.
2 - 8		\$CONTRL	This namelist will take one card and includes the variables described in Table 2.
2 - 8		\$COEFFS	This namelist will take more than one card and includes the variables listed in Tables 2 and 3.
1 - 10	F 10.0	XI	The position of the ballast weight relative to the origin of the body axis coordinates. (feet).
11 - 20	F 10.0	YI	
21 - 30	F 10.0	ZI	



Columns	Format	Symbol	Description
31 - 40	F 10.0	MASS	The rate at which the particular ballast weight is removed (pounds per second).
41 - 45	I 5	MAXI	The number of time steps during which a particular ballast weight is removed. There is one card of this type for each position from which ballast is removed.





### A - 3 Description of the Lists

The following tables contain the NAMELISTS used by the program.

TABLE 2

#### NAMELISTS

Name List/INCOND/

PROGRAM VARIABLE	USUAL NOMENCLATURE	DEFINITION & UNITS
ISTEP		The step number
DT	$\Delta t$	The time interval used during deballasting (seconds)
TIME	$t$	The time elapsed since ascent commenced (seconds)
XE	$x_E$	The x component of the distance traveled relative to the inertial origin (feet)
YE	$y_E$	The y component of the distance traveled relative to the inertial origin (feet)
ZE	$z_E$	The z component of the distance traveled relative to the inertial origin (feet)
PHI	$\phi$	The angle of roll (radians)
THETA	$\theta$	The angle of pitch (radians)
PSI	$\psi$	The angle of yaw (radians)



PROGRAM VARIABLE	USUAL NOTATION	DEFINITION & UNITS
VEARTH	$\vec{x}$	The vehicle vector of translational velocity in inertial coordinates (feet per second)
WEARTH	$\vec{\phi}$	The vehicle vector of angular velocity in inertial coordinates (radians per second)
BVEL	$\vec{v}$	The vehicle vector of translational velocity in the Body axis system (feet per second)
BROT	$\vec{w}$	The vehicle vector of angular velocity in the Body axis system (radians per second)
WT	W	The vehicle weight (pounds)
XG	$x_G$	The x components of the CG vector (feet)
YG	$y_G$	The y component of the CG vector (feet)
ZG	$z_G$	The z component of the CG vector (feet)
B	B	The vehicle buoyant force (pounds)
XB	$x_B$	The x component of the CB vector (feet)
YB	$y_B$	The y component of the CB vector (feet)
ZB	$z_B$	The z component of the CB vector (feet)
IXX	$I_{xx}$	The mass moment of inertia about the x axis (slugs)
IYY	$I_{yy}$	The mass moment of inertia about the y axis (slugs)
IZZ	$I_{zz}$	The mass moment of inertia about the z axis (slugs)







Name List/COEFFS/

PROGRAM VARIABLE	USUAL NOMENCLATURE	DEFINITION & UNITS
XEFF	$X_{EFF}$	The X component of the effector forces (pounds)
YEFF	$Y_{EFF}$	The Y component of the effector forces (pounds)
ZEFF	$Z_{EFF}$	The Z component of the effector forces (pounds)
KEFF	$K_{EFF}$	The K component of the effector forces (pounds)
MEFF	$M_{EFF}$	The M component of the effector forces (pounds)
NEFF	$N_{EFF}$	The N component of the effector forces (pounds)

Name List/COEFFS/

X	$X_{ij}$	Longitudinal force coefficients for a vehicle moving ahead
XA	$XA_{ij}$	Longitudinal force coefficients for a vehicle moving astern
Y	$Y_{ij}$	Lateral force coefficients for a vehicle moving ahead
YA	$YA_{ij}$	Lateral force coefficients for a vehicle moving astern
Z	$Z_{ij}$	Normal force coefficients for a vehicle moving ahead
ZA	$ZA_{ij}$	Normal force coefficients for a vehicle moving astern





FROM/TO VARIABLE	USUAL NOMENCLATURE	DEFINITIONS & UNITS
K	$K_{ij}$	Roll Moment force coefficients for a vehicle moving ahead
KA	$KA_{ij}$	Roll Moment force coefficients for a vehicle moving astern
M	$M_{ij}$	Pitch Moment force coefficients for a vehicle moving ahead
MA	$MA_{ij}$	Pitch Moment force coefficients for a vehicle moving astern
N	$N_{ij}$	Yaw Moment force coefficients for a vehicle moving ahead
NA	$NA_{ij}$	Yaw Moment force coefficients for a vehicle moving astern

The subscripts  $i, j$  refer to the possible combinations of the body velocities and accelerations as described in Table 3.



TABLE 3

## COEFFICIENTS

PROGRAM	STANDARD (RINDC) SUBSCRIPT NOTATION					
SUBSCRIPT	X, XA	Y, YA	Z, ZA	K, KA	H, HA	N, NA
1	uu	v v	u or *	v v	u	v v
2	vv	v	vv	v	vv	
3	ww		w w	vw	w v	vw
4		vu	w	uu or *	w	v
5		uu or *	w		uw	uu or *
6			ww		w	
7	$\dot{u}$	$\dot{v}$	$\dot{u}$	$\dot{v}$	$\dot{u}$	$\dot{v}$
8	$\dot{w}$	p	$\dot{w}$	p	$\dot{w}$	vr
9	uq	r	vp	r	vp	up
10	vr	vq	vr	vq	vr	vq
11	wq	wp	q	wp	q	p
12		wr	w q	wr	w q	r
13						v r
14	qq	$\dot{p}$	$\dot{q}$	$\dot{p}$	$\dot{q}$	$\dot{p}$
15	rr	$\dot{r}$	pp	$\dot{r}$	pp	$\dot{r}$
16	rp	pq	qq	p p	q q	r r
17	$\dot{q}$	qr	rr	pq	rr	pq
18			rp	qr	rp	qr







```

1  ISTART = ISTEP
   POSIT(3,ISTEP) = XF
   POSIT(4,ISTEP) = YE
   POSIT(5,ISTEP) = ZE
   POSIT(6,ISTEP) = PHI
   POSIT(7,ISTEP) = THLTA
   POSIT(8,ISTEP) = PSI
   U = 3VEL(1)
   V = 3VEL(2)
   W = 3VEL(3)
   P = 3ROT(1)
   Q = 3ROT(2)
   R = 3ROT(3)
   CONST = 32.17405
   G = GAMMA * VOLUME
   CALL COEFF
   DPA(5,500) (XI(1),YI(1),ZI(1),DMASS(1),IMAXI(1),I=1,IMAX)
   DO 2 I=1,IMAX
2  DMASS(I) = DMASS(I) * DT
   VPR = V0 * P
   ZR = Z0 * Q
   XPR = X0 * R
   ISTEP = ISTEP + 1
   IF (ISTEP .LE. ISTEP8) CALL BALAST
   IF (ISTEP .GT. ISTEP8) DT = DTB
   CALL FVDTG
   CALL TAJEG
   CALL POSITN
   XE = POSIT(3,ISTEP)
   YE = POSIT(4,ISTEP)
   ZE = POSIT(5,ISTEP)
   CALL INCEND
   IF (TIME .GT. TFINAL) GO TO 9999
   IF (POSIT(8,ISTEP) .GE. ZZERO) GO TO 9999
   GO TO 1
9999 WRITE(7,10000)
      ISTEP = ISTEP

```































```

AV(5,4) = IXZ - V(14)
AM(1,5) = - X(17)
AV(2,5) = C*0
AM(3,5) = - V*ASS * XG - Z(14)
A(4,5) = C*0
AV(5,5) = IYY - J(14)
AM(6,5) = C*0
AM(1,6) = - V*ASS * YG
AV(2,6) = - V*ASS * YG - V(15)
AM(3,6) = C*0
AV(4,6) = IXZ - K(15)
AV(5,6) = C*0
AM(6,6) = IZZ - W(15)
INVT AV
CALL INV(AV,6,D,LL,LN)
RETURN
END

```

C









AVV=ABS(SORT(VV+10))

UAU=U+A\*I

PAF=2\*ABS(P)

CAJ=2\*ABS(C)

RAZ=2\*ABS(R)

UAJ=U+AV

VAV = V\*AV

VAJ=V\*AJ

VAI=V\*AI

IAJ=I\*AJ

IAJ=I\*AJ

CAJ=C\*AJ

CAV = C\*AV

RAJ=R\*AJ

CAV=2\*ABS(V)

VAVJ=V\*AV

IAVJ=I\*AV

SIGJ = 1.0

IF( .NOT. C.EQ. 0 ) SIGJ = -1.0

IF( J.LT. 0.500 ) GO TO 5

XUV) = V\*ASS\*(VR - VC + XC\*(C0 + C1) - Y1\*(C2 - C3) + Z(11)\*

2\*(1 - C1) + X(2)\*(VR - VC + XC\*(C0 + C1) + X(13)\*C3) +

3\*(X(11)\*C0 + X(14)\*C1) + X(17)\*C2 + X(19)\*C4) +

VUV) = V\*ASS\*(C0 - C1 + VC\*(C1 + C2) + X(2)\*C3 + X(4)\*

2\*(1 - C1) + V\*V1 + V(2)\*C1 + JV\*(C2)\*C1 + Y(4)\*

2\*(C1 - C2) + Y(1)\*C3 + X(11)\*C4 + V(11)\*C5 + V(12)\*C6 +

4\*(13)\*C7 + Y(16)\*C8 + X(17)\*C9 + X(19)\*C10) + 2\*AV

ZUV) = V\*ASS\*(C1 - C2 + C3\*(C1 + C2) - X(3)\*C4 - X(5)\*C6) +

2\*(C1 - C2) + Z(7)\*C3 + VJ + Z(11)\*C4 + Z(13)\*C5 + Z(15)\*C6 +

3\*(C3)\*ABS(VAV) + Z(11)\*YJ + Y(11)\*C8 + V(11)\*C9 + Z(12)\*C10

4\*(VJ)\*ABS(C1)\*SIGJ + Z(15)\*C11 + Z(17)\*C12) + 2\*AV

5 + Z(11)\*C13

XUV) = -IXZ\*(C0 + (VJ - IZ1)\*C1 -

2\*(V\*ASS\*(Z3\*(C0 - C1) + VG\*(VJ - C1) + K(1)\*VAV) +

2\*(K(2)\*IV + Y(3)\*VJ + K(1)\*C1 + K(13)\*C4 + K(15)\*C6 +

4\*(K(11)\*C2 + K(12)\*C3 + K(16)\*C7 + K(17)\*C8) + K(19)\*C10

5 + K(1)\*C13



$$\begin{aligned}
& \text{WAV} = -IXZ * (RR - PP) + (IZZ - IXX) * RP - \\
& 2 \text{VYASS} * (YG * (UG - VP) + ZG * (UG - VP)) + M(1) * UJ + \\
& 3 \text{V}(2) * VV + M(3) * VAV + V(4) * U + V(5) * ABS ( VAV ) + \\
& 4 \text{V}(6) * JAV + M(9) * VP + V(10) * VU + M(11) * UJ + V(12) * AV + \\
& 5 \text{U} + V(15) * PP + M(16) * UJ + V(17) * UJ + V(14) * PP \\
& \text{WAV} = -IXZ * UJ + ( IXX - IVV ) * P - \\
& 2 \text{VYASS} * ( YG * ( VR - VC ) + ZG * ( UG - VP ) ) + M(1) * VAV + \\
& 3 \text{V}(2) * UV + M(3) * VU + M(9) * UJ + V(10) * UJ + \\
& 4 \text{M}(11) * UJ + M(12) * UJ + M(13) * VU + V(16) * UJ + \\
& 5 \text{V}(17) * PP + M(18) * UJ + V(14) * UJ + V(5) * UJ \\
& \text{GT TO 10} \\
& 5 \text{XFPV} = VYASS * ( VU - VC + XG * ( UJ + PP ) - VG * PP - VG * RP ) + \\
& 2 \text{XV}(1) * UJ + XV(2) * VV + XV(3) * UJ + XA(9) * UJ + XA(10) * \\
& 3 \text{V}(11) * UJ + XV(14) * UJ + XA(15) * UJ + XA(16) * UJ + \\
& \text{WAV} = VYASS * ( UJ - UJ + VG * ( UJ + PP ) - VG * UJ - VG * UJ ) + \\
& 2 \text{V}(1) * VAV + V(2) * UJ + V(3) * UJ + V(4) * UJ + V(5) * UJ + \\
& 3 \text{V}(6) * UJ + V(10) * UJ + V(11) * UJ + V(12) * UJ + \\
& 4 \text{V}(13) * UJ + V(15) * UJ + V(17) * UJ + V(14) * UJ + \\
& 5 \text{VYASS} * ( UJ - UJ + ZG * ( UJ + PP ) - VG * UJ - VG * UJ ) + \\
& 2 \text{Z}(1) * UJ + ZV(2) * VV + ZV(3) * VU + ZV(4) * UJ + ZV(5) * UJ + \\
& 3 \text{ZV}(6) * UJ + ZV(10) * UJ + ZV(11) * UJ + ZV(12) * UJ + ZV(13) * UJ + \\
& 4 \text{V}(15) * UJ + ZV(17) * UJ + ZV(14) * UJ + ZV(16) * UJ + \\
& 5 \text{ZV}(18) * UJ \\
& \text{XFPV} = -IXZ * PP + ( IVV - IZZ ) * UJ - \\
& 2 \text{VYASS} * ( ZG * ( UJ - VP ) + VG * ( UJ - VP ) ) + XA(1) * VAV + \\
& 3 \text{XV}(2) * UJ + XV(3) * VU + XV(4) * UJ + XA(9) * UJ + XA(10) * UJ + \\
& 4 \text{XV}(11) * UJ + XV(12) * UJ + XA(16) * UJ + XA(17) * UJ + XA(18) * UJ + \\
& 5 \text{XV}(19) * UJ \\
& \text{WAV} = -IXZ * ( UJ - PP ) + ( IZZ - IXX ) * UJ - \\
& 2 \text{VYASS} * ( XG * ( UJ - VP ) + ZG * ( UJ - VP ) ) + M(1) * UJ + \\
& 3 \text{V}(2) * VV + V(3) * VAV + V(4) * UJ + V(5) * UJ + V(6) * UJ + \\
& 4 \text{V}(7) * UJ + V(10) * UJ + V(11) * UJ + V(12) * UJ + V(13) * UJ + \\
& 5 \text{V}(14) * UJ + V(15) * UJ + V(16) * UJ + V(17) * UJ + V(18) * UJ + \\
& \text{WAV} = -IXZ * UJ + ( IXX - IVV ) * UJ - \\
& 2 \text{VYASS} * ( YG * ( VU - UJ ) + XG * ( UJ - PP ) ) + M(1) * VAV + \\
& 3 \text{V}(2) * UV + M(3) * VU + V(10) * UJ + V(11) * UJ + V(12) * UJ + \\
& 4 \text{V}(13) * UJ + V(15) * UJ + V(17) * UJ + V(14) * UJ + V(5) * UJ + \\
& 5 \text{V}(16) * UJ + V(18) * UJ + V(19) * UJ + V(20) * UJ + V(21) * UJ +
\end{aligned}$$





















## APPENDIX B

### TEST VEHICLE GEOMETRIC AND CONTROL CHARACTERISTICS

The stability and control coefficients used in the computer simulation of a free ascent trajectory come from a report on the stability and control characteristics of the Deep Submergence Rescue Vehicle (see ref 15). These coefficients were obtained using a model with propeller running, which violates one of the restrictions originally imposed on the problem. This, however, presents no problem since the coefficients with propeller running can be assumed to represent some fictitious vehicle without propeller running. This fictitious vehicle would be similar to the DSRV but would effectively have additional lifting surface on fin aft.

The coefficients and derivatives, listed in Tables 4, 5, and 6, were experimentally and analytically obtained by NASA. These coefficients will be supplemented by the terms which can be estimated from the potential theory of Chapter III (see Table 7).

The drag coefficient, to be used in conjunction with the one dimensional ascent trajectory computation, is obtained from a plot of normal force coefficient as a function of angle of attack found in reference (15). This coefficient is taken as 0.025 at an angle of attack of 90 degrees.

The geometric characteristics, listed in Table 8, are again those for the DSRV and come from reference (15).

The ballast release rates come from reference (5) and are listed in Table 9. The only weights that can be released from the DSRV are the mercury from the trim and roll systems and the water contained in the variable ballast tanks. The mercury must all pass through the central reservoir tank to be dropped, therefore, the mercury release rate is limited to the









TABLE 4

## Vertical - Plane Stability and Control Derivatives

	<u>Ahead</u>	<u>Aft</u>
$H'_{\dot{q}}$	-0.011310	0.011973
$Z'_{\dot{q}}$	-0.017455	0.015420
$H'_v$	-0.000146	-0.000102
$Z'_v$	-0.031545	-0.029545
$H'_q$	-0.001573	-0.001321
$Z'_q$	-0.000130	-0.000250

TABLE 5

## Horizontal - Plane Stability and Control Derivatives

$H'_r$	-0.012497	-0.014732
$Y'_r$	0.026955	-0.016795
$K'_r$	-0.000280	0.000220
$H'_v$	0.000132	-0.000102
$Y'_v$	-0.035545	-0.030945
$X'_v$	0.000190	0.000275
$K'_r$	-0.001531	-0.001352
$Y'_r$	0.000400	-0.000290
$K'_r$	-0.000042	0.000068

Note: Positive direction of body axes considered the same for both ahead and astern motion.



TABLE 6

Stability and Control Coefficients from Curve

Fitting and from Statistics

$H_*$	0.000081	$K_*$	-0.000157
$H_v$	0.011175	$K_v$	0.002216
$H_{ w }$	0.001458	$K_{v v }$	0.001793
$H_{vw}$	-0.003419	$K_p$	-0.000037
$H_{v w }$	-0.003624	$K_p$	-0.000027
$H_{vv}$	-0.023017	$K_{p w }$	-0.000037
$Z_*$	-0.000577	$X_u$	-0.001623
$Z_v$	-0.013938	$X_{uu}$	-0.007172
$Z_{ w }$	0.003037	$X_{vv}$	0.017510
$Z_{vw}$	-0.020773	$X_{vw}$	0.000000
$Z_{v w }$	-0.060248	$Y_v$	-0.067306
$Z_{vv}$	-0.032739	$Y_{v v }$	-0.173505
$H_v$	-0.020053	$H_{v v }$	0.000003



TABLE 7

Coefficients Estimated on the Basis of Potential Theory

	<u>Abundant</u>	<u>Abundant</u>
X <sub>qq</sub>	-0.000130	-0.000250
X <sub>rr</sub>	-0.000100	-0.000280
Y <sub>vp</sub>	0.031545	0.029515
Y <sub>pq</sub>	0.000130	0.000250
Z <sub>vp</sub>	-0.035545	-0.038915
Z <sub>rp</sub>	0.000400	-0.000280
K <sub>vw</sub>	0.004000	0.009400
K <sub>vq</sub>	0.000270	-0.000530
K <sub>vr</sub>	-0.000270	0.000530
Y <sub>pq</sub>	0.000012	-0.000060
K <sub>qr</sub>	0.000012	-0.000031
H <sub>vp</sub>	-0.000100	0.000200
H <sub>rr</sub>	0.000012	-0.000033
H <sub>rr</sub>	0.000012	-0.000038
H <sub>rp</sub>	0.001439	0.008260
H <sub>vp</sub>	-0.000130	-0.000250
N <sub>p</sub>	-0.000042	0.000058
N <sub>pq</sub>	-0.001421	-0.001229
N <sub>qr</sub>	0.000042	-0.000058



TABLE 8

## GEOMETRIC CHARACTERISTICS

Overall length, ft	49.333
Maximum beam, ft	8.167
Wetted surface area, sq ft	1318.2
Volume, cu ft	2186.1
Displacement of hull form	62.46
Longitudinal distance of CG to FP, ft	23.109
Longitudinal distance of CB to FP, ft	23.109
Height of CG above baseline, ft	3.783
Height of CB above baseline, ft	3.917
Moment of inertia about x - axis, slug - ft <sup>2</sup>	3,316.0
Moment of inertia about y - axis, slug - ft <sup>2</sup>	560,000.0
Moment of inertia about z - axis, slug - ft <sup>2</sup>	560,000.0





TABLE 9

## JETTING PATTERN

TANK	LOCATION (ft)			JET. WEIGHT (lb)	FLOW RATE (lb/sec)
	x	y	z		
1	- 3.425	0.0	3.10	2651.3	35.233
2	- 3.425	2.21	-2.24	2651.3	35.233
3	- 3.425	-2.21	-2.24	2651.3	35.233
4	18.9	0.0	-2.816	419.2	10.15
5	-18.6	0.0	-2.458	419.2	10.15
6	12.708	0.0	-2.44	200.0	0.4275
7	-12.308	0.0	-2.26	200.0	0.4275



## APPENDIX C

### INPUT AND OUTPUT FOR TEST VERSION 1

The following pages contain selected input and output from the computer simulations. Because of the large number of cycles required to simulate a trajectory, it was decided to include only that output necessary to support the conclusions reached in Chapter IV.



C - 1 Acc at Test by Air

Time increment during deballasting .5 sec

Time increment after deballasting 1.0 sec

Initial roll angle 0.0 deg

All ballast removed



STEP	DT	TIME	X	Y	Z	PHI	THETA	PSI
1	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00
2	0.50	1.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.50	1.50	0.00	0.00	0.00	0.00	0.00	0.00
4	0.50	2.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.50	2.50	0.00	0.00	0.00	0.00	0.00	0.00
6	0.50	3.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.50	3.50	0.00	0.00	0.00	0.00	0.00	0.00
8	0.50	4.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.50	4.50	0.00	0.00	0.00	0.00	0.00	0.00
10	0.50	5.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.50	5.50	0.00	0.00	0.00	0.00	0.00	0.00
12	0.50	6.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.50	6.50	0.00	0.00	0.00	0.00	0.00	0.00
14	0.50	7.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.50	7.50	0.00	0.00	0.00	0.00	0.00	0.00
16	0.50	8.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.50	8.50	0.00	0.00	0.00	0.00	0.00	0.00
18	0.50	9.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.50	9.50	0.00	0.00	0.00	0.00	0.00	0.00
20	0.50	10.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.50	10.50	0.00	0.00	0.00	0.00	0.00	0.00
22	0.50	11.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.50	11.50	0.00	0.00	0.00	0.00	0.00	0.00
24	0.50	12.00	0.00	0.00	0.00	0.00	0.00	0.00
25	0.50	12.50	0.00	0.00	0.00	0.00	0.00	0.00
26	0.50	13.00	0.00	0.00	0.00	0.00	0.00	0.00
27	0.50	13.50	0.00	0.00	0.00	0.00	0.00	0.00
28	0.50	14.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.50	14.50	0.00	0.00	0.00	0.00	0.00	0.00
30	0.50	15.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.50	15.50	0.00	0.00	0.00	0.00	0.00	0.00
32	0.50	16.00	0.00	0.00	0.00	0.00	0.00	0.00
33	0.50	16.50	0.00	0.00	0.00	0.00	0.00	0.00
34	0.50	17.00	0.00	0.00	0.00	0.00	0.00	0.00





STEP	TIME	V	Y	Z	PHI	THETA	PSI
35	17.00	-0.0	0.0	-3.8	0.0	-0.03	0.0
36	17.50	-0.1	0.0	-4.1	0.0	-0.03	0.0
37	18.00	-0.1	0.0	-4.4	0.0	-0.03	0.0
38	18.50	-0.1	0.0	-4.8	0.0	-0.03	0.0
39	19.00	-0.1	0.0	-5.2	0.0	-0.04	0.0
40	19.50	-0.1	0.0	-5.6	0.0	-0.04	0.0
41	20.00	-0.1	0.0	-6.0	0.0	-0.04	0.0
42	20.50	-0.1	0.0	-6.5	0.0	-0.04	0.0
43	21.00	-0.1	0.0	-7.0	0.0	-0.05	0.0
44	21.50	-0.2	0.0	-7.5	0.0	-0.05	0.0
45	22.00	-0.2	0.0	-8.0	0.0	-0.05	0.0
46	22.50	-0.2	0.0	-8.5	0.0	-0.05	0.0
47	23.00	-0.2	0.0	-9.1	0.0	-0.06	0.0
48	23.50	-0.2	0.0	-9.7	0.0	-0.06	0.0
49	24.00	-0.3	0.0	-10.3	0.0	-0.06	0.0
50	24.50	-0.3	0.0	-10.9	0.0	-0.06	0.0
51	25.00	-0.3	0.0	-11.5	0.0	-0.07	0.0
52	25.50	-0.4	0.0	-12.2	0.0	-0.07	0.0
53	26.00	-0.4	0.0	-12.9	0.0	-0.07	0.0
54	26.50	-0.5	0.0	-13.7	0.0	-0.07	0.0
55	27.00	-0.5	0.0	-14.4	0.0	-0.08	0.0
56	27.50	-0.6	0.0	-15.2	0.0	-0.08	0.0
57	28.00	-0.6	0.0	-16.0	0.0	-0.08	0.0
58	28.50	-0.7	0.0	-16.9	0.0	-0.08	0.0
59	29.00	-0.7	0.0	-17.7	0.0	-0.09	0.0
60	29.50	-0.9	0.0	-18.5	0.0	-0.09	0.0
61	30.00	-0.9	0.0	-19.5	0.0	-0.09	0.0
62	30.50	-1.0	0.0	-20.4	0.0	-0.10	0.0
63	31.00	-1.0	0.0	-21.3	0.0	-0.10	0.0
64	31.50	-1.1	0.0	-22.0	0.0	-0.10	0.0
65	32.00	-1.2	0.0	-22.8	0.0	-0.10	0.0
66	32.50	-1.3	0.0	-23.4	0.0	-0.10	0.0
67	33.00	-1.4	0.0	-24.5	0.0	-0.11	0.0
68	33.50	-1.5	0.0	-25.8	0.0	-0.11	0.0



STEP	DT	TIME	X	Y	T	PHI	THETA	PSI
171	0.50	95.00	-31.2	0.0	-255.9	0.0	-0.01	0.0
172	0.50	95.50	-31.7	0.0	-253.0	0.0	-0.02	0.0
173	0.50	96.00	-32.1	0.0	-251.8	0.0	-0.02	0.0
174	0.50	96.50	-32.5	0.0	-249.9	0.0	-0.02	0.0
175	0.50	97.00	-33.0	0.0	-247.9	0.0	-0.04	0.0
176	0.50	97.50	-33.5	0.0	-245.9	0.0	-0.04	0.0
177	0.50	98.00	-34.0	0.0	-243.9	0.0	-0.04	0.0
178	0.50	98.50	-34.5	0.0	-241.9	0.0	-0.05	0.0
179	0.50	99.00	-35.0	0.0	-239.9	0.0	-0.05	0.0
180	0.50	99.50	-35.5	0.0	-237.9	0.0	-0.05	0.0
181	0.50	100.00	-36.0	0.0	-235.9	0.0	-0.05	0.0
182	0.50	100.50	-36.5	0.0	-233.9	0.0	-0.05	0.0
183	0.50	101.00	-37.0	0.0	-231.9	0.0	-0.05	0.0
184	0.50	101.50	-37.5	0.0	-229.9	0.0	-0.05	0.0
185	0.50	102.00	-38.0	0.0	-227.9	0.0	-0.05	0.0
186	0.50	102.50	-38.5	0.0	-225.9	0.0	-0.05	0.0
187	0.50	103.00	-39.0	0.0	-223.9	0.0	-0.04	0.0
188	0.50	103.50	-39.5	0.0	-221.9	0.0	-0.04	0.0
189	0.50	104.00	-40.0	0.0	-219.9	0.0	-0.04	0.0
190	0.50	104.50	-40.5	0.0	-217.9	0.0	-0.03	0.0
191	0.50	105.00	-41.0	0.0	-215.9	0.0	-0.03	0.0
192	0.50	105.50	-41.5	0.0	-213.9	0.0	-0.02	0.0
193	0.50	106.00	-42.0	0.0	-211.9	0.0	-0.01	0.0
194	0.50	106.50	-42.5	0.0	-209.9	0.0	0.00	0.0
195	0.50	107.00	-43.0	0.0	-207.9	0.0	0.01	0.0
196	0.50	107.50	-43.5	0.0	-205.9	0.0	0.02	0.0
197	0.50	108.00	-44.0	0.0	-203.9	0.0	0.03	0.0
198	0.50	108.50	-44.5	0.0	-201.9	0.0	0.04	0.0
199	0.50	109.00	-45.0	0.0	-199.9	0.0	0.05	0.0
200	0.50	109.50	-45.5	0.0	-197.9	0.0	0.05	0.0
201	0.50	110.00	-46.0	0.0	-195.9	0.0	0.05	0.0
202	0.50	110.50	-46.5	0.0	-193.9	0.0	0.05	0.0
203	0.50	111.00	-47.0	0.0	-191.9	0.0	0.04	0.0
204	0.50	111.50	-47.5	0.0	-189.9	0.0	0.04	0.0



SORD	DT	TIME	Y	V	Z	CHI	THETA	PSI
205	0.50	102.50	-44.1	0.0	-362.8	0.0	0.06	0.0
206	0.50	102.50	-42.4	0.0	-365.9	0.0	0.06	0.0
207	0.50	103.00	-43.9	0.0	-369.0	0.0	0.05	0.0
208	0.50	103.50	-40.1	0.0	-372.1	0.0	0.04	0.0
209	0.50	104.00	-40.4	0.0	-375.2	0.0	0.04	0.0
210	0.50	104.50	-40.7	0.0	-378.3	0.0	0.03	0.0
211	0.50	105.00	-53.1	0.0	-381.3	0.0	0.02	0.0
212	0.50	105.50	-50.4	0.0	-384.4	0.0	0.01	0.0
213	0.50	106.00	-51.3	0.0	-387.4	0.0	0.01	0.0
214	0.50	106.50	-51.3	0.0	-390.5	0.0	0.01	0.0
215	0.50	107.00	-51.7	0.0	-393.6	0.0	0.02	0.0
216	0.50	107.50	-52.2	0.0	-396.6	0.0	0.04	0.0
217	0.50	108.00	-52.7	0.0	-399.7	0.0	0.05	0.0
218	0.50	108.50	-53.2	0.0	-402.8	0.0	0.05	0.0
219	0.50	109.00	-53.9	0.0	-406.0	0.0	0.05	0.0
220	0.50	109.50	-54.4	0.0	-409.1	0.0	0.07	0.0
221	0.50	110.00	-55.1	0.0	-412.2	0.0	0.08	0.0
222	0.50	110.50	-55.7	0.0	-415.3	0.0	0.09	0.0
223	0.50	111.00	-56.3	0.0	-418.7	0.0	0.09	0.0
224	0.50	111.50	-57.1	0.0	-421.8	0.0	0.09	0.0
225	0.50	112.00	-57.7	0.0	-425.2	0.0	0.09	0.0
226	0.50	112.50	-58.6	0.0	-428.3	0.0	0.08	0.0
227	0.50	113.00	-59.2	0.0	-431.8	0.0	0.07	0.0
228	0.50	113.50	-59.9	0.0	-435.1	0.0	0.06	0.0
229	0.50	114.00	-60.3	0.0	-438.4	0.0	0.05	0.0
230	0.50	114.50	-61.0	0.0	-441.8	0.0	0.05	0.0
231	0.50	115.00	-62.1	0.0	-445.1	0.0	0.05	0.0
232	0.50	115.50	-62.6	0.0	-448.5	0.0	0.03	0.0
233	0.50	116.00	-63.2	0.0	-451.9	0.0	0.02	0.0
234	0.50	116.50	-63.7	0.0	-455.2	0.0	0.01	0.0
235	1.00	117.00	-64.0	0.0	-458.6	0.0	0.01	0.0
236	1.00	117.50	-64.8	0.0	-462.0	0.0	0.04	0.0
237	1.00	118.00	-65.3	0.0	-465.3	0.0	0.05	0.0
238	1.00	118.50	-66.4	0.0	-475.2	0.0	0.06	0.0
239	1.00	119.00	-67.1	0.0	-481.7	0.0	0.10	0.0



STEP	DT	TIME	X	Y	Z	DHI	THETA	PSI
273	1.00	155.50	-94.2	0.0	-711.6	0.0	-0.27	0.0
274	1.00	156.50	-96.3	0.0	-719.9	0.0	-0.30	0.0
275	1.00	157.50	-98.3	0.0	-728.7	0.0	-0.21	0.0
276	1.00	158.50	-99.0	0.0	-737.5	0.0	-0.11	0.0
277	1.00	159.50	-101.1	0.0	-746.5	0.0	-0.01	0.0
278	1.00	160.50	-101.7	0.0	-755.1	0.0	0.10	0.0
279	1.00	161.50	-101.5	0.0	-763.4	0.0	0.20	0.0
280	1.00	162.50	-100.7	0.0	-771.5	0.0	0.28	0.0
281	1.00	163.50	-99.1	0.0	-779.3	0.0	0.33	0.0
282	1.00	164.50	-97.0	0.0	-786.9	0.0	0.39	0.0
283	1.00	165.50	-94.9	0.0	-794.0	0.0	0.29	0.0
284	1.00	166.50	-92.7	0.0	-800.6	0.0	0.21	0.0
285	1.00	167.50	-90.7	0.0	-805.7	0.0	0.12	0.0
286	1.00	168.50	-88.0	0.0	-812.4	0.0	0.02	0.0
287	1.00	169.50	-84.7	0.0	-817.7	0.0	0.09	0.0
288	1.00	170.50	-80.9	0.0	-822.2	0.0	0.20	0.0
289	1.00	171.50	-76.7	0.0	-827.3	0.0	0.31	0.0
290	1.00	172.50	-72.1	0.0	-832.0	0.0	0.43	0.0
291	1.00	173.50	-66.1	0.0	-836.0	0.0	0.53	0.0
292	1.00	174.50	-59.3	0.0	-840.7	0.0	0.58	0.0
293	1.00	175.50	-51.1	0.0	-844.9	0.0	0.59	0.0
294	1.00	176.50	-42.9	0.0	-848.9	0.0	0.50	0.0
295	1.00	177.50	-33.9	0.0	-852.9	0.0	0.50	0.0
296	1.00	178.50	-24.6	0.0	-857.1	0.0	0.51	0.0
297	1.00	179.50	-14.7	0.0	-861.3	0.0	0.43	0.0
298	1.00	180.50	-4.9	0.0	-865.3	0.0	0.33	0.0
299	1.00	181.50	5.0	0.0	-869.1	0.0	0.22	0.0
300	1.00	182.50	15.0	0.0	-872.9	0.0	0.11	0.0
301	1.00	183.50	25.0	0.0	-876.3	0.0	0.02	0.0
302	1.00	184.50	35.0	0.0	-879.3	0.0	0.14	0.0
303	1.00	185.50	45.0	0.0	-882.7	0.0	0.24	0.0
304	1.00	186.50	55.0	0.0	-886.3	0.0	0.30	0.0
305	1.00	187.50	65.0	0.0	-890.1	0.0	0.31	0.0
306	1.00	188.50	75.0	0.0	-894.1	0.0	0.28	0.0
307	1.00	189.50	85.0	0.0	-898.0	0.0	0.18	0.0





ST-50	95	TIME	X	Y	Z	PHI	THETA	DST
207	1.00	189.50	-83.0	0.0	-079.0	0.0	0.09	0.0
208	1.00	191.40	-71.6	0.0	-077.7	0.0	-0.01	0.0
209	1.00	191.50	-70.7	0.0	-082.0	0.0	-0.12	0.0
210	1.00	192.80	-70.4	0.0	-080.1	0.0	-0.23	0.0
211	1.00	193.80	-77.7	0.0	-083.2	0.0	-0.35	0.0
212	1.00	194.50	-77.6	0.0	-080.7	0.0	-0.47	0.0
213	1.00	195.50	-79.2	0.0	-1004.7	0.0	-0.56	0.0
214	1.00	196.50	-79.2	0.0	-1011.4	0.0	-0.62	0.0
215	1.00	197.80	-80.4	0.0	-1013.8	0.0	-0.64	0.0
216	1.00	198.80	-11.3	0.0	-1026.9	0.0	-0.62	0.0
217	1.00	199.80	-83.1	0.0	-1035.6	0.0	-0.57	0.0
218	1.00	200.80	-84.4	0.0	-1046.4	0.0	-0.40	0.0
219	1.00	201.80	-65.5	0.0	-1054.4	0.0	-0.40	0.0
220	1.00	202.80	-66.6	0.0	-1066.1	0.0	-0.20	0.0
221	1.00	203.80	-66.3	0.0	-1073.7	0.0	-0.17	0.0
222	1.00	204.80	-86.0	0.0	-1083.1	0.0	-0.05	0.0
223	1.00	205.80	-66.1	0.0	-1092.2	0.0	0.07	0.0
224	1.00	206.80	-64.4	0.0	-1100.0	0.0	0.20	0.0
225	1.00	207.80	-81.0	0.0	-1100.0	0.0	0.26	0.0
226	1.00	208.80	-78.0	0.0	-1116.0	0.0	0.27	0.0
227	1.00	209.80	-78.0	0.0	-1124.3	0.0	0.25	0.0
228	1.00	210.80	-72.8	0.0	-1131.0	0.0	0.17	0.0
229	1.00	211.80	-68.6	0.0	-1127.4	0.0	0.09	0.0
230	1.00	212.80	-67.1	0.0	-1142.0	0.0	-0.01	0.0
231	1.00	213.80	-61.0	0.0	-1143.5	0.0	-0.12	0.0
232	1.00	214.80	-60.4	0.0	-1152.5	0.0	-0.23	0.0
233	1.00	215.80	-62.4	0.0	-1158.7	0.0	-0.24	0.0
234	1.00	216.80	-62.0	0.0	-1164.0	0.0	-0.46	0.0
235	1.00	217.80	-60.2	0.0	-1168.0	0.0	-0.50	0.0
236	1.00	218.80	-60.1	0.0	-1176.7	0.0	-0.67	0.0
237	1.00	219.80	-64.1	0.0	-1183.6	0.0	-0.66	0.0
238	1.00	220.80	-65.0	0.0	-1191.5	0.0	-0.65	0.0
239	1.00	221.80	-66.6	0.0	-1200.1	0.0	-0.60	0.0
240	1.00	222.80	-67.7	0.0	-1200.0	0.0	-0.80	0.0



STEP	CT	TIME	Y	X	Z	PHI	THETA	PSI
409	1.00	201.50	-13.7	0.0	-1730.2	0.0	-0.32	0.0
410	1.00	202.50	-14.1	0.0	-1720.9	0.0	-0.20	0.0
411	1.00	203.50	-14.3	0.0	-1740.2	0.0	-0.08	0.0
412	1.00	204.50	-13.2	0.0	-1750.4	0.0	0.04	0.0
413	1.00	205.50	-11.5	0.0	-1767.0	0.0	0.16	0.0
414	1.00	206.50	-9.9	0.0	-1775.2	0.0	0.24	0.0
415	1.00	207.50	-8.9	0.0	-1780.1	0.0	0.27	0.0
416	1.00	208.50	-7.5	0.0	-1790.5	0.0	0.25	0.0
417	1.00	209.50	-7.7	0.0	-1797.4	0.0	0.19	0.0
418	1.00	210.50	-7.7	0.0	-1800.7	0.0	0.00	0.0



STEP	TIME	U EARTH	V EARTH	W EARTH	P EARTH	Q EARTH	R EARTH
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	1.00	0.00	0.00	0.00	0.00	0.00	0.00
4	1.50	0.00	0.00	0.00	0.00	0.00	0.00
5	2.00	0.00	0.00	0.00	0.00	0.00	0.00
6	2.50	0.00	0.00	0.00	0.00	0.00	0.00
7	3.00	0.00	0.00	0.00	0.00	0.00	0.00
8	3.50	0.00	0.00	0.00	0.00	0.00	0.00
9	4.00	0.00	0.00	0.00	0.00	0.00	0.00
10	4.50	0.00	0.00	0.00	0.00	0.00	0.00
11	5.00	0.00	0.00	0.00	0.00	0.00	0.00
12	5.50	0.00	0.00	0.00	0.00	0.00	0.00
13	6.00	0.00	0.00	0.00	0.00	0.00	0.00
14	6.50	0.00	0.00	0.00	0.00	0.00	0.00
15	7.00	0.00	0.00	0.00	0.00	0.00	0.00
16	7.50	0.00	0.00	0.00	0.00	0.00	0.00
17	8.00	0.00	0.00	0.00	0.00	0.00	0.00
18	8.50	0.00	0.00	0.00	0.00	0.00	0.00
19	9.00	0.00	0.00	0.00	0.00	0.00	0.00
20	9.50	0.00	0.00	0.00	0.00	0.00	0.00
21	10.00	0.00	0.00	0.00	0.00	0.00	0.00
22	10.50	0.00	0.00	0.00	0.00	0.00	0.00
23	11.00	0.00	0.00	0.00	0.00	0.00	0.00
24	11.50	0.00	0.00	0.00	0.00	0.00	0.00
25	12.00	0.00	0.00	0.00	0.00	0.00	0.00
26	12.50	0.00	0.00	0.00	0.00	0.00	0.00
27	13.00	0.00	0.00	0.00	0.00	0.00	0.00
28	13.50	0.00	0.00	0.00	0.00	0.00	0.00
29	14.00	0.00	0.00	0.00	0.00	0.00	0.00
30	14.50	0.00	0.00	0.00	0.00	0.00	0.00
31	15.00	0.00	0.00	0.00	0.00	0.00	0.00
32	15.50	0.00	0.00	0.00	0.00	0.00	0.00
33	16.00	0.00	0.00	0.00	0.00	0.00	0.00
34	16.50	0.00	0.00	0.00	0.00	0.00	0.00



STEP	TIME	U FAITH	V FAITH	W FAITH	D FAITH	Q FAITH	P FAITH
35	17.00	-0.014	0.0	-0.643	0.0	-0.004	0.0
36	17.50	-0.035	0.0	-0.606	0.0	-0.004	0.0
37	18.00	-0.018	0.0	-0.722	0.0	-0.004	0.0
38	18.50	-0.009	0.0	-0.760	0.0	-0.004	0.0
39	19.00	-0.023	0.0	-0.800	0.0	-0.004	0.0
40	19.50	-0.025	0.0	-0.840	0.0	-0.004	0.0
41	20.00	-0.038	0.0	-0.881	0.0	-0.004	0.0
42	20.50	-0.032	0.0	-0.923	0.0	-0.005	0.0
43	21.00	-0.030	0.0	-0.965	0.0	-0.005	0.0
44	21.50	-0.030	0.0	-1.003	0.0	-0.005	0.0
45	22.00	-0.046	0.0	-1.052	0.0	-0.005	0.0
46	22.50	-0.047	0.0	-1.097	0.0	-0.005	0.0
47	23.00	-0.051	0.0	-1.142	0.0	-0.005	0.0
48	23.50	-0.053	0.0	-1.186	0.0	-0.005	0.0
49	24.00	-0.041	0.0	-1.230	0.0	-0.005	0.0
50	24.50	-0.037	0.0	-1.272	0.0	-0.005	0.0
51	25.00	-0.050	0.0	-1.330	0.0	-0.005	0.0
52	25.50	-0.070	0.0	-1.378	0.0	-0.005	0.0
53	26.00	-0.065	0.0	-1.430	0.0	-0.005	0.0
54	26.50	-0.060	0.0	-1.480	0.0	-0.005	0.0
55	27.00	-0.060	0.0	-1.520	0.0	-0.005	0.0
56	27.50	-0.077	0.0	-1.570	0.0	-0.005	0.0
57	28.00	-0.080	0.0	-1.630	0.0	-0.005	0.0
58	28.50	-0.082	0.0	-1.682	0.0	-0.005	0.0
59	29.00	-0.082	0.0	-1.730	0.0	-0.005	0.0
60	29.50	-0.080	0.0	-1.780	0.0	-0.005	0.0
61	30.00	-0.080	0.0	-1.840	0.0	-0.005	0.0
62	30.50	-0.080	0.0	-1.900	0.0	-0.005	0.0
63	31.00	-0.080	0.0	-1.960	0.0	-0.005	0.0
64	31.50	-0.080	0.0	-2.020	0.0	-0.004	0.0
65	32.00	-0.080	0.0	-2.080	0.0	-0.004	0.0
66	32.50	-0.080	0.0	-2.140	0.0	-0.004	0.0
67	33.00	-0.080	0.0	-2.200	0.0	-0.004	0.0
68	33.50	-0.080	0.0	-2.260	0.0	-0.005	0.0





STEP	TIME	U	V	W	EARTH	F	EARTH	R	EARTH
205	102.00	-0.632	0.0	-6.230	0.0	0.0	-0.004	0.0	0.0
206	102.50	-0.635	0.0	-6.212	0.0	0.0	-0.007	0.0	0.0
207	103.00	-0.637	0.0	-6.190	0.0	0.0	-0.010	0.0	0.0
208	103.50	-0.634	0.0	-6.160	0.0	0.0	-0.013	0.0	0.0
209	104.00	-0.635	0.0	-6.140	0.0	0.0	-0.014	0.0	0.0
210	104.50	-0.631	0.0	-6.115	0.0	0.0	-0.018	0.0	0.0
211	105.00	-0.715	0.0	-6.122	0.0	0.0	-0.023	0.0	0.0
212	105.50	-0.750	0.0	-6.121	0.0	0.0	-0.021	0.0	0.0
213	106.00	-1.003	0.0	-6.137	0.0	0.0	-0.022	0.0	0.0
214	106.50	-0.662	0.0	-6.101	0.0	0.0	-0.022	0.0	0.0
215	107.00	-0.630	0.0	-6.122	0.0	0.0	-0.023	0.0	0.0
216	107.50	-0.635	0.0	-6.141	0.0	0.0	-0.022	0.0	0.0
217	108.00	-1.111	0.0	-6.100	0.0	0.0	-0.020	0.0	0.0
218	108.50	-1.152	0.0	-6.020	0.0	0.0	-0.019	0.0	0.0
219	109.00	-1.220	0.0	-6.237	0.0	0.0	-0.016	0.0	0.0
220	109.50	-1.251	0.0	-6.315	0.0	0.0	-0.013	0.0	0.0
221	110.00	-1.227	0.0	-6.455	0.0	0.0	-0.009	0.0	0.0
222	110.50	-1.235	0.0	-6.459	0.0	0.0	-0.009	0.0	0.0
223	111.00	-1.237	0.0	-6.502	0.0	0.0	-0.002	0.0	0.0
224	111.50	-1.430	0.0	-6.548	0.0	0.0	0.005	0.0	0.0
225	112.00	-1.430	0.0	-6.601	0.0	0.0	0.006	0.0	0.0
226	112.50	-1.431	0.0	-6.620	0.0	0.0	0.015	0.0	0.0
227	113.00	-1.423	0.0	-6.633	0.0	0.0	0.017	0.0	0.0
228	113.50	-1.424	0.0	-6.640	0.0	0.0	0.020	0.0	0.0
229	114.00	-1.424	0.0	-6.727	0.0	0.0	0.022	0.0	0.0
230	114.50	-1.437	0.0	-6.715	0.0	0.0	0.024	0.0	0.0
231	115.00	-1.438	0.0	-6.725	0.0	0.0	0.025	0.0	0.0
232	115.50	-1.437	0.0	-6.726	0.0	0.0	0.027	0.0	0.0
233	116.00	-1.439	0.0	-6.715	0.0	0.0	0.028	0.0	0.0
234	116.50	-1.437	0.0	-6.700	0.0	0.0	0.023	0.0	0.0
235	117.00	-1.436	0.0	-6.685	0.0	0.0	0.025	0.0	0.0
236	117.50	-1.436	0.0	-6.562	0.0	0.0	0.021	0.0	0.0
237	118.00	-1.430	0.0	-6.675	0.0	0.0	0.016	0.0	0.0
238	118.50	-1.430	0.0	-6.675	0.0	0.0	0.016	0.0	0.0



STEP	TIME	III BODY	V BODY	6 BODY	9 BODY	5 BODY	R BODY
1	0.50	0.00	0.00	0.00	0.00	0.00	0.00
2	0.50	0.00	0.00	0.00	0.00	0.00	0.00
3	1.50	0.00	0.00	0.00	0.00	0.00	0.00
4	1.50	0.00	0.00	0.00	0.00	0.00	0.00
5	2.50	0.00	0.00	0.00	0.00	0.00	0.00
6	2.50	0.00	0.00	0.00	0.00	0.00	0.00
7	3.50	0.00	0.00	0.00	0.00	0.00	0.00
8	3.50	0.00	0.00	0.00	0.00	0.00	0.00
9	4.50	0.00	0.00	0.00	0.00	0.00	0.00
10	4.50	0.00	0.00	0.00	0.00	0.00	0.00
11	5.50	0.00	0.00	0.00	0.00	0.00	0.00
12	5.50	0.00	0.00	0.00	0.00	0.00	0.00
13	6.50	0.00	0.00	0.00	0.00	0.00	0.00
14	6.50	0.00	0.00	0.00	0.00	0.00	0.00
15	7.50	0.00	0.00	0.00	0.00	0.00	0.00
16	7.50	0.00	0.00	0.00	0.00	0.00	0.00
17	8.50	0.00	0.00	0.00	0.00	0.00	0.00
18	8.50	0.00	0.00	0.00	0.00	0.00	0.00
19	9.50	0.00	0.00	0.00	0.00	0.00	0.00
20	9.50	0.00	0.00	0.00	0.00	0.00	0.00
21	10.50	0.00	0.00	0.00	0.00	0.00	0.00
22	10.50	0.00	0.00	0.00	0.00	0.00	0.00
23	11.50	0.00	0.00	0.00	0.00	0.00	0.00
24	11.50	0.00	0.00	0.00	0.00	0.00	0.00
25	12.50	0.00	0.00	0.00	0.00	0.00	0.00
26	12.50	0.00	0.00	0.00	0.00	0.00	0.00
27	13.50	0.00	0.00	0.00	0.00	0.00	0.00
28	13.50	0.00	0.00	0.00	0.00	0.00	0.00
29	14.50	0.00	0.00	0.00	0.00	0.00	0.00
30	14.50	0.00	0.00	0.00	0.00	0.00	0.00
31	15.50	0.00	0.00	0.00	0.00	0.00	0.00
32	15.50	0.00	0.00	0.00	0.00	0.00	0.00
33	16.50	0.00	0.00	0.00	0.00	0.00	0.00
34	16.50	0.00	0.00	0.00	0.00	0.00	0.00



STEP	TIME	U	V	W	D	S	P
		BODY	BODY	BODY	BODY	BODY	BODY
35	17.00	-0.031	0.000	-0.647	0.000	-0.004	0.000
36	17.15	-0.030	0.000	-0.696	0.000	-0.004	0.000
37	17.30	-0.040	0.000	-0.721	0.000	-0.004	0.000
38	17.45	-0.045	0.000	-0.750	0.000	-0.004	0.000
39	17.59	-0.050	0.000	-0.769	0.000	-0.004	0.000
40	18.00	-0.057	0.000	-0.803	0.000	-0.004	0.000
41	18.15	-0.063	0.000	-0.870	0.000	-0.004	0.000
42	18.30	-0.070	0.000	-0.921	0.000	-0.005	0.000
43	18.45	-0.077	0.000	-0.963	0.000	-0.005	0.000
44	18.59	-0.085	0.000	-1.005	0.000	-0.005	0.000
45	19.00	-0.090	0.000	-1.040	0.000	-0.005	0.000
46	19.15	-0.102	0.000	-1.063	0.000	-0.005	0.000
47	19.30	-0.112	0.000	-1.139	0.000	-0.005	0.000
48	19.45	-0.122	0.000	-1.163	0.000	-0.005	0.000
49	19.59	-0.133	0.000	-1.200	0.000	-0.005	0.000
50	20.00	-0.144	0.000	-1.273	0.000	-0.005	0.000
51	20.15	-0.153	0.000	-1.322	0.000	-0.005	0.000
52	20.30	-0.160	0.000	-1.372	0.000	-0.005	0.000
53	20.45	-0.163	0.000	-1.413	0.000	-0.005	0.000
54	20.59	-0.166	0.000	-1.467	0.000	-0.005	0.000
55	21.00	-0.171	0.000	-1.506	0.000	-0.005	0.000
56	21.15	-0.173	0.000	-1.549	0.000	-0.005	0.000
57	21.30	-0.172	0.000	-1.616	0.000	-0.005	0.000
58	21.45	-0.170	0.000	-1.666	0.000	-0.005	0.000
59	21.59	-0.177	0.000	-1.717	0.000	-0.005	0.000
60	22.00	-0.180	0.000	-1.760	0.000	-0.005	0.000
61	22.15	-0.183	0.000	-1.800	0.000	-0.005	0.000
62	22.30	-0.182	0.000	-1.871	0.000	-0.005	0.000
63	22.45	-0.182	0.000	-1.920	0.000	-0.005	0.000
64	22.59	-0.187	0.000	-1.971	0.000	-0.004	0.000
65	23.00	-0.192	0.000	-2.000	0.000	-0.004	0.000
66	23.15	-0.193	0.000	-2.043	0.000	-0.004	0.000
67	23.30	-0.195	0.000	-2.100	0.000	-0.004	0.000
68	23.45	-0.194	0.000	-2.150	0.000	-0.004	0.000



STEP	TIME	U ppm	V ppm	W ppm	P ppm	Q ppm	R ppm
171	85.00	-1.075	0.0	-5.091	0.0	-0.011	0.0
172	85.50	-1.084	0.0	-5.090	0.0	-0.011	0.0
173	86.00	-1.091	0.0	-5.089	0.0	-0.011	0.0
174	86.50	-1.098	0.0	-5.085	0.0	-0.011	0.0
175	87.00	-1.105	0.0	-5.079	0.0	-0.010	0.0
176	87.50	-1.109	0.0	-5.080	0.0	-0.009	0.0
177	88.00	-1.100	0.0	-6.028	0.0	-0.009	0.0
178	88.50	-1.139	0.0	-7.090	0.0	-0.007	0.0
179	89.00	-1.135	0.0	-6.080	0.0	-0.005	0.0
180	89.50	-1.144	0.0	-6.121	0.0	-0.003	0.0
181	90.00	-1.174	0.0	-6.154	0.0	-0.001	0.0
182	90.50	-1.195	0.0	-6.180	0.0	0.001	0.0
183	91.00	-1.125	0.0	-6.221	0.0	0.002	0.0
184	91.50	-1.103	0.0	-6.257	0.0	0.005	0.0
185	92.00	-1.130	0.0	-6.301	0.0	0.007	0.0
186	92.50	-1.154	0.0	-6.324	0.0	0.009	0.0
187	93.00	-1.165	0.0	-6.350	0.0	0.011	0.0
188	93.50	-1.146	0.0	-6.380	0.0	0.012	0.0
189	94.00	-1.108	0.0	-6.400	0.0	0.014	0.0
190	94.50	-1.123	0.0	-6.400	0.0	0.014	0.0
191	95.00	-1.126	0.0	-6.450	0.0	0.016	0.0
192	95.50	-1.120	0.0	-6.450	0.0	0.016	0.0
193	96.00	-1.105	0.0	-6.470	0.0	0.016	0.0
194	96.50	-1.124	0.0	-6.470	0.0	0.016	0.0
195	97.00	-1.090	0.0	-6.470	0.0	0.016	0.0
196	97.50	-1.015	0.0	-6.460	0.0	0.015	0.0
197	98.00	-1.071	0.0	-6.450	0.0	0.016	0.0
198	98.50	-1.001	0.0	-6.443	0.0	0.012	0.0
199	99.00	-0.946	0.0	-6.424	0.0	0.011	0.0
200	99.50	-0.900	0.0	-6.400	0.0	0.009	0.0
201	100.00	-0.801	0.0	-6.337	0.0	0.007	0.0
202	100.50	-0.785	0.0	-6.300	0.0	0.006	0.0
203	101.00	-0.700	0.0	-6.210	0.0	0.004	0.0
204	101.50	-0.678	0.0	-6.200	0.0	-0.001	0.0





STEP	TIME	I PCV	V PCV	X PCV	P PCV	Q PCV	R PCV
205	102.00	-1.260	0.0	-5.266	0.0	-0.004	0.0
206	102.50	-0.242	0.0	-5.230	0.0	-0.007	0.0
207	103.00	-0.204	0.0	-5.214	0.0	-0.010	0.0
208	103.50	-0.222	0.0	-5.102	0.0	-0.013	0.0
209	104.00	-0.278	0.0	-5.172	0.0	-0.016	0.0
210	104.50	-0.400	0.0	-5.157	0.0	-0.019	0.0
211	105.00	-0.537	0.0	-5.144	0.0	-0.020	0.0
212	105.50	-0.680	0.0	-5.135	0.0	-0.021	0.0
213	106.00	-0.781	0.0	-5.130	0.0	-0.022	0.0
214	106.50	-0.873	0.0	-5.120	0.0	-0.023	0.0
215	107.00	-1.002	0.0	-5.112	0.0	-0.023	0.0
216	107.50	-1.124	0.0	-5.111	0.0	-0.022	0.0
217	108.00	-1.266	0.0	-5.154	0.0	-0.020	0.0
218	108.50	-1.338	0.0	-5.171	0.0	-0.018	0.0
219	109.00	-1.510	0.0	-5.102	0.0	-0.010	0.0
220	109.50	-1.620	0.0	-5.210	0.0	-0.012	0.0
221	110.00	-1.729	0.0	-5.260	0.0	-0.000	0.0
222	110.50	-1.914	0.0	-5.300	0.0	-0.000	0.0
223	111.00	-2.070	0.0	-5.320	0.0	-0.002	0.0
224	111.50	-2.200	0.0	-5.360	0.0	-0.002	0.0
225	112.00	-2.364	0.0	-5.470	0.0	-0.004	0.0
226	112.50	-2.551	0.0	-5.460	0.0	-0.010	0.0
227	113.00	-2.690	0.0	-5.500	0.0	-0.010	0.0
228	113.50	-2.800	0.0	-5.560	0.0	-0.017	0.0
229	114.00	-2.919	0.0	-5.500	0.0	-0.020	0.0
230	114.50	-3.024	0.0	-5.520	0.0	-0.022	0.0
231	115.00	-3.160	0.0	-5.657	0.0	-0.024	0.0
232	115.50	-3.300	0.0	-5.602	0.0	-0.026	0.0
233	116.00	-3.450	0.0	-5.700	0.0	-0.027	0.0
234	116.50	-3.500	0.0	-5.700	0.0	-0.028	0.0
235	117.00	-3.600	0.0	-5.700	0.0	-0.030	0.0
236	117.50	-3.700	0.0	-5.700	0.0	-0.025	0.0
237	118.00	-3.800	0.0	-5.700	0.0	-0.023	0.0
238	118.50	-3.900	0.0	-5.700	0.0	-0.023	0.0
239	119.00	-4.000	0.0	-5.700	0.0	-0.014	0.0



step	time	W	V	W	P	Q	P
307	100.50	3.570	0.0	5.219	0.0	-0.000	0.0
308	100.50	3.570	0.0	5.219	0.0	-0.107	0.0
309	101.50	1.540	0.0	5.165	0.0	-0.111	0.0
310	102.50	0.455	0.0	5.275	0.0	-0.116	0.0
311	103.50	1.140	0.0	5.220	0.0	-0.120	0.0
312	104.50	2.151	0.0	5.253	0.0	-0.111	0.0
313	105.50	3.500	0.0	5.250	0.0	-0.092	0.0
314	106.50	4.751	0.0	5.215	0.0	-0.040	0.0
315	107.50	5.535	0.0	5.515	0.0	-0.053	0.0
316	108.50	6.100	0.0	5.330	0.0	-0.040	0.0
317	109.50	6.235	0.0	4.543	0.0	-0.047	0.0
318	110.50	6.100	0.0	7.200	0.0	-0.050	0.0
319	111.50	6.100	0.0	6.000	0.0	-0.102	0.0
320	112.50	4.433	0.0	6.633	0.0	-0.114	0.0
321	113.50	3.106	0.0	6.100	0.0	-0.122	0.0
322	114.50	1.903	0.0	6.170	0.0	-0.125	0.0
323	115.50	2.716	0.0	6.351	0.0	-0.123	0.0
324	116.50	2.700	0.0	8.140	0.0	-0.103	0.0
325	117.50	4.101	0.0	7.200	0.0	-0.050	0.0
326	118.50	5.100	0.0	6.633	0.0	-0.031	0.0
327	119.50	5.100	0.0	5.000	0.0	-0.057	0.0
328	120.50	6.760	0.0	5.500	0.0	-0.050	0.0
329	121.50	7.000	0.0	5.500	0.0	-0.007	0.0
330	122.50	7.000	0.0	6.000	0.0	-0.105	0.0
331	123.50	1.001	0.0	5.100	0.0	-0.110	0.0
332	124.50	2.001	0.0	5.100	0.0	-0.110	0.0
333	125.50	3.000	0.0	5.201	0.0	-0.114	0.0
334	126.50	2.200	0.0	5.200	0.0	-0.009	0.0
335	127.50	1.471	0.0	5.200	0.0	-0.050	0.0
336	128.50	5.373	0.0	5.400	0.0	-0.06	0.0
337	129.50	5.373	0.0	5.400	0.0	-0.06	0.0
338	130.50	5.373	0.0	5.400	0.0	-0.06	0.0
339	131.50	5.373	0.0	5.400	0.0	-0.06	0.0
340	132.50	5.373	0.0	5.400	0.0	-0.06	0.0
341	133.50	5.373	0.0	5.400	0.0	-0.06	0.0



STEP	TIME	U mV	V mV	W mV	P mV	Q mV	R mV
409	201.50	-4.591	0.0	-9.622	0.0	0.113	0.0
410	202.50	-3.186	0.0	-0.251	0.0	0.121	0.0
411	203.50	-1.462	0.0	-0.160	0.0	0.125	0.0
412	204.50	0.470	0.0	-9.051	0.0	0.124	0.0
413	205.50	2.405	0.0	-0.267	0.0	0.100	0.0
414	206.50	4.210	0.0	-7.476	0.0	0.059	0.0
415	207.50	5.110	0.0	-6.670	0.0	-0.002	0.0
416	208.50	5.150	0.0	-6.049	0.0	-0.052	0.0
417	209.50	4.650	0.0	-5.628	0.0	-0.080	0.0
418	210.50	2.306	0.0	-5.371	0.0	-0.065	0.0



STEP	TIME	U DOT	V DOT	W DOT	X DOT	Y DOT	Z DOT	0 DOT	1 DOT	2 DOT
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	1.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
27	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	1.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	1.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	1.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	1.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	1.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00





STEP	TIME	Q DOT	V DOT	P DOT	Q DOT	P DOT
25	17.35	0.00	0.00	0.00	0.00	0.00
26	17.40	0.00	0.00	0.00	0.00	0.00
27	17.45	0.00	0.00	0.00	0.00	0.00
28	17.50	0.00	0.00	0.00	0.00	0.00
29	17.55	0.00	0.00	0.00	0.00	0.00
30	18.00	0.00	0.00	0.00	0.00	0.00
31	18.05	0.00	0.00	0.00	0.00	0.00
32	18.10	0.00	0.00	0.00	0.00	0.00
33	18.15	0.00	0.00	0.00	0.00	0.00
34	18.20	0.00	0.00	0.00	0.00	0.00
35	18.25	0.00	0.00	0.00	0.00	0.00
36	18.30	0.00	0.00	0.00	0.00	0.00
37	18.35	0.00	0.00	0.00	0.00	0.00
38	18.40	0.00	0.00	0.00	0.00	0.00
39	18.45	0.00	0.00	0.00	0.00	0.00
40	18.50	0.00	0.00	0.00	0.00	0.00
41	18.55	0.00	0.00	0.00	0.00	0.00
42	19.00	0.00	0.00	0.00	0.00	0.00
43	19.05	0.00	0.00	0.00	0.00	0.00
44	19.10	0.00	0.00	0.00	0.00	0.00
45	19.15	0.00	0.00	0.00	0.00	0.00
46	19.20	0.00	0.00	0.00	0.00	0.00
47	19.25	0.00	0.00	0.00	0.00	0.00
48	19.30	0.00	0.00	0.00	0.00	0.00
49	19.35	0.00	0.00	0.00	0.00	0.00
50	19.40	0.00	0.00	0.00	0.00	0.00
51	19.45	0.00	0.00	0.00	0.00	0.00
52	19.50	0.00	0.00	0.00	0.00	0.00
53	19.55	0.00	0.00	0.00	0.00	0.00
54	20.00	0.00	0.00	0.00	0.00	0.00
55	20.05	0.00	0.00	0.00	0.00	0.00
56	20.10	0.00	0.00	0.00	0.00	0.00
57	20.15	0.00	0.00	0.00	0.00	0.00
58	20.20	0.00	0.00	0.00	0.00	0.00
59	20.25	0.00	0.00	0.00	0.00	0.00
60	20.30	0.00	0.00	0.00	0.00	0.00











CTP	TIME	U DDT	V DDT	W DDT	P DDT	Q DDT	R DDT
270	155.50	-	0.0	-0.520	0.0	0.024	0.0
274	156.50	0.151	0.0	-0.504	0.0	0.019	0.0
275	157.50	0.710	0.0	-0.564	0.0	0.012	0.0
276	158.50	1.59	0.0	-0.450	0.0	0.000	0.0
277	159.50	1.353	0.0	-0.100	0.0	0.005	0.0
278	160.50	1.570	0.0	0.006	0.0	-0.000	0.0
279	161.50	1.635	0.0	0.397	0.0	-0.006	0.0
280	162.50	1.500	0.0	0.570	0.0	-0.020	0.0
281	163.50	1.127	0.0	0.680	0.0	-0.048	0.0
282	164.50	0.447	0.0	0.600	0.0	-0.049	0.0
283	165.50	0.150	0.0	0.457	0.0	-0.038	0.0
284	166.50	0.512	0.0	0.350	0.0	-0.022	0.0
285	167.50	0.700	0.0	0.154	0.0	-0.013	0.0
286	168.50	0.971	0.0	0.006	0.0	-0.008	0.0
287	169.50	0.507	0.0	0.000	0.0	-0.000	0.0
288	170.50	1.100	0.0	0.020	0.0	-0.005	0.0
289	171.50	1.280	0.0	0.057	0.0	-0.008	0.0
290	172.50	1.347	0.0	0.027	0.0	-0.003	0.0
291	173.50	1.330	0.0	0.010	0.0	0.032	0.0
292	174.50	1.100	0.0	0.070	0.0	0.042	0.0
293	175.50	0.805	0.0	0.060	0.0	0.070	0.0
294	176.50	0.400	0.0	0.015	0.0	0.005	0.0
295	177.50	0.760	0.0	0.000	0.0	0.026	0.0
296	178.50	0.311	0.0	0.700	0.0	0.010	0.0
297	179.50	0.710	0.0	0.700	0.0	0.015	0.0
298	180.50	1.100	0.0	0.500	0.0	0.011	0.0
299	181.50	1.000	0.0	0.000	0.0	0.007	0.0
300	182.50	1.010	0.0	0.200	0.0	0.002	0.0
301	183.50	1.000	0.0	0.420	0.0	-0.004	0.0
302	184.50	1.000	0.0	0.600	0.0	-0.000	0.0
303	185.50	1.000	0.0	0.700	0.0	-0.057	0.0
304	186.50	1.000	0.0	0.700	0.0	-0.050	0.0
305	187.50	1.000	0.0	0.500	0.0	-0.040	0.0
306	188.50	1.000	0.0	0.300	0.0	-0.022	0.0





Step	Time	U DOT	V DOT	W DOT	X DOT	Y DOT	Z DOT
400	201.50	0.374	0.0	-0.665	0.0	0.0	0.0
410	202.50	1.235	0.0	-0.449	0.0	0.0	0.0
421	203.50	1.753	0.0	-0.110	0.0	0.0	0.0
432	204.50	1.241	0.0	0.070	0.0	0.0	0.0
443	205.50	2.517	0.0	0.028	0.0	0.0	0.0
454	206.50	1.715	0.0	0.700	0.0	0.0	0.0
465	207.50	1.002	0.0	0.707	0.0	0.0	0.0
476	208.50	1.060	0.0	0.420	0.0	0.0	0.0
487	209.50	-0.607	0.0	0.000	0.0	0.0	0.0
498	-0.170	-0.170	0.0	0.055	0.0	0.0	0.0











STEP	TIME	HEIGHT	X5	YC	ZC	STAYANCE
205	102.00	126754.4	0.067	0.0	-0.052	129910.4
206	102.50	126753.0	0.067	0.0	-0.052	129910.4
207	103.00	126753.5	0.067	0.0	-0.052	129910.4
208	103.50	126753.1	0.067	0.0	-0.052	129910.4
209	104.00	126752.6	0.067	0.0	-0.052	129910.4
210	104.50	126752.2	0.067	0.0	-0.052	129910.4
211	105.00	126751.7	0.067	0.0	-0.052	129910.4
212	105.50	126751.3	0.067	0.0	-0.052	129910.4
213	106.00	126750.8	0.067	0.0	-0.052	129910.4
214	106.50	126750.4	0.067	0.0	-0.052	129910.4
215	107.00	126750.0	0.067	0.0	-0.052	129910.4
216	107.50	126749.5	0.067	0.0	-0.052	129910.4
217	108.00	126749.1	0.067	0.0	-0.052	129910.4
218	108.50	126748.7	0.067	0.0	-0.052	129910.4
219	109.00	126748.2	0.067	0.0	-0.052	129910.4
220	109.50	126747.8	0.067	0.0	-0.052	129910.4
221	110.00	126747.4	0.067	0.0	-0.052	129910.4
222	110.50	126746.9	0.067	0.0	-0.052	129910.4
223	111.00	126746.5	0.067	0.0	-0.052	129910.4
224	111.50	126746.1	0.067	0.0	-0.052	129910.4
225	112.00	126745.6	0.067	0.0	-0.052	129910.4
226	112.50	126745.2	0.067	0.0	-0.052	129910.4
227	113.00	126744.7	0.067	0.0	-0.052	129910.4
228	113.50	126744.3	0.067	0.0	-0.052	129910.4
229	114.00	126743.8	0.067	0.0	-0.052	129910.4
230	114.50	126743.4	0.067	0.0	-0.052	129910.4
231	115.00	126742.9	0.067	0.0	-0.052	129910.4
232	115.50	126742.5	0.067	0.0	-0.052	129910.4
233	116.00	126742.1	0.067	0.0	-0.052	129910.4
234	116.50	126741.7	0.067	0.0	-0.052	129910.4
235	117.00	126741.3	0.067	0.0	-0.052	129910.4
236	117.50	126740.8	0.067	0.0	-0.052	129910.4
237	118.00	126740.4	0.067	0.0	-0.052	129910.4
238	118.50	126740.0	0.067	0.0	-0.052	129910.4
239	119.00	126739.6	0.067	0.0	-0.052	129910.4













STEP	DT	TIME	Y	Y	7	PHI	THETA	PSI
35	0.10	3.40	0.00	0.00	0.00	0.06	0.00	0.00
36	0.10	3.50	0.00	0.00	0.00	0.07	0.00	0.00
37	0.10	3.60	0.00	0.00	0.00	0.08	0.00	0.00
38	0.10	3.70	0.00	0.00	0.00	0.09	0.00	0.00
39	0.10	3.80	0.00	0.00	0.00	0.10	0.00	0.00
40	0.10	3.90	0.00	0.00	0.00	0.11	0.00	0.00
41	0.10	4.00	0.00	0.00	0.00	0.12	0.00	0.00
42	0.10	4.10	0.00	0.00	0.00	0.13	0.00	0.00
43	0.10	4.20	0.00	0.00	0.00	0.14	0.00	0.00
44	0.10	4.30	0.00	0.00	0.00	0.15	0.00	0.00
45	0.10	4.40	0.00	0.00	0.00	0.16	0.00	0.00
46	0.10	4.50	0.00	0.00	0.00	0.17	0.00	0.00
47	0.10	4.60	0.00	0.00	0.00	0.18	0.00	0.00
48	0.10	4.70	0.00	0.00	0.00	0.19	0.00	0.00
49	0.10	4.80	0.00	0.00	0.00	0.20	0.00	0.00
50	0.10	4.90	0.00	0.00	0.00	0.21	0.00	0.00
51	0.10	5.00	0.00	0.00	0.00	0.22	0.00	0.00
52	0.10	5.10	0.00	0.00	0.00	0.23	0.00	0.00
53	0.10	5.20	0.00	0.00	0.00	0.24	0.00	0.00
54	0.10	5.30	0.00	0.00	0.00	0.25	0.00	0.00
55	0.10	5.40	0.00	0.00	0.00	0.26	0.00	0.00
56	0.10	5.50	0.00	0.00	0.00	0.27	0.00	0.00
57	0.10	5.60	0.00	0.00	0.00	0.28	0.00	0.00
58	0.10	5.70	0.00	0.00	0.00	0.29	0.00	0.00
59	0.10	5.80	0.00	0.00	0.00	0.30	0.00	0.00
60	0.10	5.90	0.00	0.00	0.00	0.31	0.00	0.00
61	0.10	6.00	0.00	0.00	0.00	0.32	0.00	0.00
62	0.10	6.10	0.00	0.00	0.00	0.33	0.00	0.00
63	0.10	6.20	0.00	0.00	0.00	0.34	0.00	0.00
64	0.10	6.30	0.00	0.00	0.00	0.35	0.00	0.00
65	0.10	6.40	0.00	0.00	0.00	0.36	0.00	0.00
66	0.10	6.50	0.00	0.00	0.00	0.37	0.00	0.00
67	0.10	6.60	0.00	0.00	0.00	0.38	0.00	0.00
68	0.10	6.70	0.00	0.00	0.00	0.39	0.00	0.00



STEP	DT	TIME	X	Y	Z	PHI	THETA	PSI
103	0.10	12.20	0.00	0.00	0.00	0.15	0.01	0.00
104	0.10	12.20	0.00	0.00	0.00	0.16	0.01	0.00
105	0.10	12.40	0.00	0.00	0.00	0.16	0.01	0.00
106	0.10	12.50	0.00	0.00	0.00	0.17	0.01	0.00
107	0.10	12.60	0.00	0.00	0.00	0.17	0.01	0.00
108	0.10	12.70	0.00	0.00	0.00	0.18	0.01	0.00
109	0.10	12.80	0.00	0.00	0.00	0.18	0.01	0.00
110	0.10	12.90	0.00	0.00	0.00	0.18	0.01	0.00
111	0.10	13.00	0.00	0.00	0.00	0.19	0.01	0.00
112	0.10	13.10	0.00	0.00	0.00	0.19	0.01	0.00
113	0.10	13.20	0.00	0.00	0.00	0.19	0.01	0.00
114	0.10	13.30	0.00	0.00	0.00	0.19	0.01	0.00
115	0.10	13.40	0.00	0.00	0.00	0.19	0.01	0.00
116	0.10	13.50	0.00	0.00	0.00	0.19	0.01	0.00
117	0.10	13.60	0.00	0.00	0.00	0.19	0.01	0.00
118	0.10	13.70	0.00	0.00	0.00	0.19	0.01	0.00
119	0.10	13.80	0.00	0.00	0.00	0.18	0.01	0.00
120	0.10	13.90	0.00	0.00	0.00	0.18	0.01	0.00
121	0.10	14.00	0.00	0.00	0.00	0.17	0.01	0.00
122	0.10	14.10	0.00	0.00	0.00	0.17	0.01	0.00
123	0.10	14.20	0.00	0.00	0.00	0.16	0.01	0.00
124	0.10	14.30	0.00	0.00	0.00	0.16	0.01	0.00
125	0.10	14.40	0.00	0.00	0.00	0.15	0.01	0.00
126	0.10	14.50	0.00	0.00	0.00	0.14	0.01	0.00
127	0.10	14.60	0.00	0.00	0.00	0.14	0.01	0.00
128	0.10	14.70	0.00	0.00	0.00	0.13	0.01	0.00
129	0.10	14.80	0.00	0.00	0.00	0.12	0.01	0.00
130	0.10	14.90	0.00	0.00	0.00	0.11	0.01	0.00
131	0.10	15.00	0.00	0.00	0.00	0.10	0.01	0.00
132	0.10	15.10	0.00	0.00	0.00	0.09	0.01	0.00
133	0.10	15.20	0.00	0.00	0.00	0.08	0.01	0.00
134	0.10	15.30	0.00	0.00	0.00	0.07	0.01	0.00
135	0.10	15.40	0.00	0.00	0.00	0.06	0.01	0.00
136	0.10	15.50	0.00	0.00	0.00	0.05	0.01	0.00
137	0.10	15.60	0.00	0.00	0.00	0.04	0.01	0.00
138	0.10	15.70	0.00	0.00	0.00	0.03	0.01	0.00
139	0.10	15.80	0.00	0.00	0.00	0.02	0.01	0.00
140	0.10	15.90	0.00	0.00	0.00	0.01	0.01	0.00





STEP	DT	TIME	Y	V	Z	PHI	THETA	PSI
175	0	17.00	0.0	0.0	-3.6	-0.10	0.00	0.00
176	0	17.10	0.0	0.0	-3.7	-0.10	0.00	0.00
177	0	17.20	0.0	0.0	-3.8	-0.10	0.00	0.00
178	0	17.30	0.0	0.0	-3.9	-0.10	0.00	0.00
179	0	17.40	0.0	0.0	-4.0	-0.10	0.00	0.00
180	0	17.50	0.0	0.0	-4.1	-0.10	0.00	0.00
181	0	17.60	0.0	0.0	-4.2	-0.10	0.00	0.00
182	0	17.70	0.0	0.0	-4.3	-0.10	0.00	0.00
183	0	17.80	0.0	0.0	-4.4	-0.10	0.00	0.00
184	0	17.90	0.0	0.0	-4.5	-0.10	0.00	0.00
185	0	18.00	0.0	0.0	-4.6	-0.10	0.00	0.00
186	0	18.10	0.0	0.0	-4.7	-0.10	0.00	0.00
187	0	18.20	0.0	0.0	-4.8	-0.10	0.00	0.00
188	0	18.30	0.0	0.0	-4.9	-0.10	0.00	0.00
189	0	18.40	0.0	0.0	-5.0	-0.10	0.00	0.00
190	0	18.50	0.0	0.0	-5.1	-0.10	0.00	0.00
191	0	18.60	0.0	0.0	-5.2	-0.10	0.00	0.00
192	0	18.70	0.0	0.0	-5.3	-0.10	0.00	0.00
193	0	18.80	0.0	0.0	-5.4	-0.10	0.00	0.00
194	0	18.90	0.0	0.0	-5.5	-0.10	0.00	0.00
195	0	19.00	0.0	0.0	-5.6	-0.10	0.00	0.00
196	0	19.10	0.0	0.0	-5.7	-0.10	0.00	0.00
197	0	19.20	0.0	0.0	-5.8	-0.10	0.00	0.00
198	0	19.30	0.0	0.0	-5.9	-0.10	0.00	0.00
199	0	19.40	0.0	0.0	-6.0	-0.10	0.00	0.00
200	0	19.50	0.0	0.0	-6.1	-0.10	0.00	0.00
201	0	19.60	0.0	0.0	-6.2	-0.10	0.00	0.00
202	0	19.70	0.0	0.0	-6.3	-0.10	0.00	0.00
203	0	19.80	0.0	0.0	-6.4	-0.10	0.00	0.00
204	0	19.90	0.0	0.0	-6.5	-0.10	0.00	0.00



STEP	DT	TIME	X	Y	Z	PHI	THETA	PSI
205	0.10	20.45	0.1	0.0	-6.2	0.06	-0.04	0.00
206	0.10	20.55	0.1	0.0	-6.3	0.07	-0.05	0.00
207	0.10	20.65	0.1	0.0	-6.4	0.08	-0.06	0.00
208	0.10	20.75	0.1	0.0	-6.5	0.09	-0.05	0.00
209	0.10	20.85	0.1	0.0	-6.6	0.10	-0.05	0.00
210	0.10	20.95	0.1	0.0	-6.7	0.11	-0.05	0.00
211	0.10	21.05	0.1	0.0	-6.8	0.12	-0.05	0.00
212	0.10	21.15	0.2	0.0	-6.9	0.13	-0.05	0.00
213	0.10	21.25	0.2	0.0	-7.0	0.13	-0.05	0.00
214	0.10	21.35	0.2	0.0	-7.1	0.14	-0.05	0.00
215	0.10	21.45	0.2	0.0	-7.2	0.15	-0.05	0.00
216	0.10	21.55	0.2	0.0	-7.3	0.15	-0.05	0.00
217	0.10	21.65	0.2	0.0	-7.4	0.16	-0.05	0.00
218	0.10	21.75	0.2	0.0	-7.5	0.17	-0.05	0.00
219	0.10	21.85	0.2	0.0	-7.6	0.17	-0.05	0.00
220	0.10	21.95	0.2	0.0	-7.7	0.18	-0.05	0.00
221	0.10	22.05	0.2	0.0	-7.8	0.19	-0.05	0.00
222	0.10	22.15	0.2	0.0	-7.9	0.19	-0.05	0.00
223	0.10	22.25	0.2	0.0	-8.0	0.19	-0.05	0.00
224	0.10	22.35	0.2	0.0	-8.1	0.19	-0.05	0.00
225	0.10	22.45	0.2	0.0	-8.2	0.20	-0.05	0.00
226	0.10	22.55	0.2	0.0	-8.3	0.20	-0.05	0.00
227	0.10	22.65	0.2	0.0	-8.4	0.21	-0.05	0.00
228	0.10	22.75	0.2	0.0	-8.5	0.21	-0.05	0.00
229	0.10	22.85	0.2	0.0	-8.6	0.22	-0.05	0.00
230	0.10	22.95	0.2	0.0	-8.7	0.22	-0.05	0.00
231	0.10	23.05	0.2	0.0	-8.8	0.23	-0.05	0.00
232	0.10	23.15	0.2	0.0	-8.9	0.23	-0.05	0.00
233	0.10	23.25	0.2	0.0	-9.0	0.24	-0.05	0.00
234	0.10	23.35	0.2	0.0	-9.1	0.24	-0.05	0.00
235	0.10	23.45	0.2	0.0	-9.2	0.25	-0.05	0.00
236	0.10	23.55	0.2	0.0	-9.3	0.25	-0.05	0.00
237	0.10	23.65	0.2	0.0	-9.4	0.26	-0.05	0.00
238	0.10	23.75	0.2	0.0	-9.5	0.26	-0.05	0.00



STEP	CT	TIME	V	Z	PHI	THETA	PSI
400	0.10	40.80	0.4	-45.1	-0.15	-0.11	-0.02
401	0.10	40.90	0.4	-45.4	-0.15	-0.11	-0.02
402	0.10	41.00	0.4	-45.7	-0.15	-0.11	-0.02
403	0.10	41.10	0.4	-46.0	-0.17	-0.11	-0.02
404	0.10	41.20	0.4	-46.3	-0.17	-0.11	-0.02
405	0.10	41.30	0.4	-46.6	-0.19	-0.11	-0.02
406	0.10	41.40	0.4	-46.9	-0.19	-0.11	-0.02
407	0.10	41.50	0.4	-47.3	-0.19	-0.11	-0.02
408	0.10	41.60	0.4	-47.6	-0.20	-0.11	-0.02
409	0.10	41.70	0.4	-47.9	-0.20	-0.11	-0.02
410	0.10	41.80	0.4	-48.2	-0.21	-0.11	-0.02
411	0.10	41.90	0.4	-48.5	-0.21	-0.11	-0.02
412	0.10	42.00	0.4	-48.9	-0.21	-0.11	-0.02
413	0.10	42.10	0.4	-49.1	-0.22	-0.11	-0.02
414	0.10	42.20	0.4	-49.5	-0.22	-0.11	-0.02
415	0.10	42.30	0.4	-49.9	-0.23	-0.11	-0.02
416	0.10	42.40	0.4	-50.1	-0.23	-0.11	-0.02
417	0.10	42.50	0.3	-50.4	-0.23	-0.11	-0.02
418	0.10	42.60	0.3	-50.7	-0.23	-0.11	-0.02
419	0.10	42.70	0.3	-51.0	-0.24	-0.11	-0.02
420	0.10	42.80	0.3	-51.4	-0.24	-0.11	-0.02
421	0.10	42.90	0.3	-51.7	-0.24	-0.11	-0.02
422	0.10	43.00	0.3	-52.0	-0.24	-0.11	-0.02
423	0.10	43.10	0.3	-52.3	-0.24	-0.11	-0.02
424	0.10	43.20	0.3	-52.7	-0.24	-0.11	-0.02
425	0.10	43.30	0.3	-53.0	-0.24	-0.11	-0.02
426	0.10	43.40	0.2	-53.6	-0.24	-0.11	-0.02
427	0.10	43.50	0.2	-54.0	-0.24	-0.11	-0.02
428	0.10	43.60	0.2	-54.3	-0.24	-0.11	-0.02
429	0.10	43.70	0.2	-54.6	-0.24	-0.11	-0.02
430	0.10	43.80	0.2	-54.9	-0.24	-0.11	-0.02
431	0.10	43.90	0.1	-55.3	-0.24	-0.11	-0.02
432	0.10	44.00	0.1	-55.6	-0.24	-0.11	-0.02



STEP	DT	TIME	X	Y	Z	PHI	THETA	PSI
443	0.10	44.20	-5.1	0.1	-56.0	-0.23	-0.11	-0.01
444	0.10	44.30	-5.1	0.0	-56.3	-0.23	-0.11	-0.01
445	0.10	44.40	-5.1	0.0	-56.6	-0.23	-0.11	-0.01
446	0.10	44.50	-5.2	0.0	-57.0	-0.23	-0.11	-0.01
447	0.10	44.60	-5.2	0.0	-57.3	-0.22	-0.11	-0.01
448	0.10	44.70	-5.2	0.0	-57.7	-0.22	-0.11	-0.01
449	0.10	44.80	-5.3	0.1	-58.0	-0.21	-0.11	-0.01
450	0.10	44.90	-5.3	0.1	-58.3	-0.21	-0.11	-0.01
451	0.10	45.00	-5.4	0.1	-58.7	-0.21	-0.11	-0.01
452	0.10	45.10	-5.4	0.2	-59.0	-0.20	-0.11	-0.01
453	0.10	45.20	-5.4	0.2	-59.4	-0.20	-0.11	-0.01
454	0.10	45.30	-5.5	0.2	-59.7	-0.19	-0.11	-0.01
455	0.10	45.40	-5.5	0.2	-60.1	-0.19	-0.11	-0.01
456	0.10	45.50	-5.6	0.3	-60.4	-0.18	-0.11	-0.01
457	0.10	45.60	-5.6	0.3	-60.9	-0.18	-0.11	-0.01
458	0.10	45.70	-5.6	0.3	-61.1	-0.17	-0.11	-0.01
459	0.10	45.80	-5.7	0.3	-61.5	-0.16	-0.11	-0.01
460	0.10	45.90	-5.7	0.4	-61.8	-0.16	-0.11	-0.01
461	0.10	46.00	-5.8	0.4	-62.2	-0.15	-0.11	-0.01
462	0.10	46.10	-5.8	0.4	-62.5	-0.15	-0.11	-0.01
463	0.10	46.20	-5.8	0.5	-62.9	-0.14	-0.10	-0.01
464	0.10	46.30	-5.9	0.5	-63.2	-0.13	-0.10	-0.01
465	0.10	46.40	-5.9	0.6	-63.6	-0.13	-0.10	-0.01
466	0.10	46.50	-6.0	0.6	-64.0	-0.12	-0.10	-0.01
467	0.10	46.60	-6.0	0.6	-64.3	-0.12	-0.10	-0.01
468	0.10	46.70	-6.0	0.6	-64.7	-0.11	-0.10	-0.01
469	0.10	46.80	-6.0	0.6	-65.0	-0.11	-0.10	-0.01
470	0.10	46.90	-6.1	0.7	-65.4	-0.10	-0.10	-0.01
471	0.10	47.00	-6.1	0.7	-65.8	-0.09	-0.10	-0.01
472	0.10	47.10	-6.2	0.7	-66.1	-0.09	-0.10	-0.01
473	0.10	47.20	-6.2	0.7	-66.5	-0.08	-0.10	-0.01
474	0.10	47.30	-6.2	0.7	-66.9	-0.08	-0.10	-0.01
475	0.10	47.40	-6.2	0.8	-67.3	-0.07	-0.10	-0.01
476	0.10	47.50	-6.3	0.8	-67.6	-0.06	-0.10	-0.01





STEP	TIME	U BODY	V BODY	W BODY	D BODY	G BODY	R BODY
1	0.10	0.000	0.000	0.000	0.000	0.000	0.000
2	0.20	0.000	0.000	0.000	0.000	0.000	0.000
3	0.30	0.000	0.000	0.000	0.000	0.000	0.000
4	0.40	0.000	0.000	0.000	0.000	0.000	0.000
5	0.50	0.000	0.000	0.000	0.000	0.000	0.000
6	0.60	0.000	0.000	0.000	0.000	0.000	0.000
7	0.70	0.000	0.000	0.000	0.000	0.000	0.000
8	0.80	0.000	0.000	0.000	0.000	0.000	0.000
9	0.90	0.000	0.000	0.000	0.000	0.000	0.000
10	1.00	0.000	0.000	0.000	0.000	0.000	0.000
11	1.10	0.000	0.000	0.000	0.000	0.000	0.000
12	1.20	0.000	0.000	0.000	0.000	0.000	0.000
13	1.30	0.000	0.000	0.000	0.000	0.000	0.000
14	1.40	0.000	0.000	0.000	0.000	0.000	0.000
15	1.50	0.000	0.000	0.000	0.000	0.000	0.000
16	1.60	0.000	0.000	0.000	0.000	0.000	0.000
17	1.70	0.000	0.000	0.000	0.000	0.000	0.000
18	1.80	0.000	0.000	0.000	0.000	0.000	0.000
19	1.90	0.000	0.000	0.000	0.000	0.000	0.000
20	2.00	0.000	0.000	0.000	0.000	0.000	0.000
21	2.10	0.000	0.000	0.000	0.000	0.000	0.000
22	2.20	0.000	0.000	0.000	0.000	0.000	0.000
23	2.30	0.000	0.000	0.000	0.000	0.000	0.000
24	2.40	0.000	0.000	0.000	0.000	0.000	0.000
25	2.50	0.000	0.000	0.000	0.000	0.000	0.000
26	2.60	0.000	0.000	0.000	0.000	0.000	0.000
27	2.70	0.000	0.000	0.000	0.000	0.000	0.000
28	2.80	0.000	0.000	0.000	0.000	0.000	0.000
29	2.90	0.000	0.000	0.000	0.000	0.000	0.000
30	3.00	0.000	0.000	0.000	0.000	0.000	0.000
31	3.10	0.000	0.000	0.000	0.000	0.000	0.000
32	3.20	0.000	0.000	0.000	0.000	0.000	0.000
33	3.30	0.000	0.000	0.000	0.000	0.000	0.000
34	3.40	0.000	0.000	0.000	0.000	0.000	0.000



STEP	TIME	U BODY	V BODY	W BODY	P BODY	C BODY	P BODY
35	3.40	-0.000	0.001	-0.026	-0.094	-0.000	0.001
36	3.50	-0.000	0.002	-0.028	-0.093	-0.000	0.001
37	3.60	-0.000	0.002	-0.030	-0.091	-0.000	0.001
38	3.70	-0.000	0.002	-0.031	-0.088	-0.000	0.001
39	3.80	-0.000	0.003	-0.032	-0.085	-0.000	0.001
40	3.90	-0.000	0.003	-0.035	-0.083	-0.000	0.001
41	4.00	-0.000	0.004	-0.036	-0.080	-0.001	0.001
42	4.10	-0.000	0.004	-0.039	-0.076	-0.001	0.001
43	4.20	-0.000	0.005	-0.042	-0.073	-0.001	0.001
44	4.30	-0.000	0.005	-0.042	-0.069	-0.001	0.001
45	4.40	-0.000	0.006	-0.044	-0.065	-0.001	0.001
46	4.50	-0.000	0.006	-0.046	-0.061	-0.001	0.001
47	4.60	-0.000	0.007	-0.048	-0.056	-0.001	0.001
48	4.70	-0.000	0.007	-0.051	-0.051	-0.001	0.001
49	4.80	-0.000	0.008	-0.052	-0.046	-0.001	0.000
50	4.90	-0.000	0.008	-0.054	-0.041	-0.001	0.000
51	5.00	-0.000	0.009	-0.056	-0.036	-0.001	0.000
52	5.10	-0.000	0.010	-0.058	-0.031	-0.001	0.000
53	5.20	-0.000	0.011	-0.060	-0.026	-0.001	0.000
54	5.30	-0.000	0.011	-0.060	-0.021	-0.001	0.000
55	5.40	-0.000	0.011	-0.065	-0.015	-0.001	0.000
56	5.50	-0.000	0.011	-0.067	-0.009	-0.001	0.000
57	5.60	-0.000	0.012	-0.071	-0.004	-0.001	0.000
58	5.70	-0.000	0.012	-0.072	0.002	-0.001	0.000
59	5.80	-0.000	0.013	-0.075	0.007	-0.001	0.000
60	5.90	-0.000	0.013	-0.078	0.013	-0.001	0.000
61	6.00	-0.000	0.013	-0.080	0.019	-0.001	0.000
62	6.10	-0.000	0.014	-0.083	0.024	-0.001	0.000
63	6.20	-0.000	0.016	-0.086	0.030	-0.001	0.000
64	6.30	-0.000	0.014	-0.090	0.035	-0.001	0.001
65	6.40	-0.000	0.014	-0.091	0.040	-0.001	0.001
66	6.50	-0.000	0.014	-0.092	0.045	-0.001	0.001
67	6.60	-0.000	0.014	-0.097	0.051	-0.001	0.001
68	6.70	-0.000	0.016	-0.101	0.055	-0.001	0.001



STEP	TIME	U BODY	V BODY	W BODY	S BODY	Q BODY	R BODY
103	11.20	-0.003	-0.032	-0.231	0.061	-0.002	-0.001
104	11.25	-0.004	-0.033	-0.235	0.056	-0.002	-0.001
105	11.30	-0.006	-0.035	-0.239	0.051	-0.003	-0.002
106	11.35	-0.004	-0.027	-0.244	0.046	-0.002	-0.000
107	11.40	-0.006	-0.029	-0.240	0.041	-0.003	-0.000
108	11.45	-0.004	-0.026	-0.233	0.035	-0.002	-0.000
109	11.50	-0.004	-0.042	-0.257	0.031	-0.002	-0.000
110	11.55	-0.005	-0.043	-0.252	0.024	-0.002	-0.000
111	11.60	-0.005	-0.045	-0.266	0.019	-0.003	-0.000
112	11.65	-0.005	-0.045	-0.271	0.019	-0.003	-0.000
113	11.70	-0.005	-0.047	-0.276	0.017	-0.003	-0.000
114	11.75	-0.005	-0.048	-0.281	0.011	-0.002	-0.000
115	11.80	-0.005	-0.047	-0.286	-0.004	-0.002	-0.000
116	11.85	-0.006	-0.050	-0.291	-0.010	-0.003	-0.000
117	11.90	-0.006	-0.051	-0.296	-0.016	-0.003	-0.000
118	11.95	-0.007	-0.051	-0.301	-0.022	-0.003	-0.001
119	12.00	-0.007	-0.051	-0.306	-0.027	-0.003	-0.001
120	12.05	-0.007	-0.051	-0.311	-0.032	-0.003	-0.001
121	12.10	-0.008	-0.051	-0.317	-0.039	-0.003	-0.001
122	12.15	-0.009	-0.051	-0.322	-0.049	-0.003	-0.001
123	12.20	-0.009	-0.050	-0.328	-0.049	-0.003	-0.001
124	12.25	-0.009	-0.040	-0.332	-0.054	-0.003	-0.001
125	12.30	-0.009	-0.040	-0.339	-0.059	-0.003	-0.001
126	12.35	-0.009	-0.047	-0.346	-0.064	-0.003	-0.001
127	12.40	-0.009	-0.046	-0.350	-0.068	-0.003	-0.001
128	12.45	-0.009	-0.044	-0.356	-0.073	-0.003	-0.001
129	12.50	-0.010	-0.043	-0.360	-0.077	-0.003	-0.001
130	12.55	-0.010	-0.041	-0.366	-0.081	-0.003	-0.001
131	12.60	-0.010	-0.039	-0.374	-0.085	-0.003	-0.001
132	12.65	-0.011	-0.036	-0.381	-0.089	-0.003	-0.001
133	12.70	-0.011	-0.034	-0.386	-0.091	-0.003	-0.001
134	12.75	-0.012	-0.031	-0.392	-0.094	-0.003	-0.001
135	12.80	-0.012	-0.029	-0.399	-0.097	-0.003	-0.001
136	12.85	-0.012	-0.028	-0.404	-0.099	-0.003	-0.001



STEP	TIME	U BODY	V BODY	W BODY	P BODY	C BODY	R BODY
171	17.00	-0.034	0.119	-0.623	0.001	-0.004	-0.000
172	17.05	-0.035	0.110	-0.620	0.007	-0.004	-0.000
173	17.20	-0.036	0.111	-0.637	0.013	-0.004	-0.001
174	17.25	-0.037	0.111	-0.674	0.019	-0.004	-0.002
175	17.40	-0.039	0.111	-0.652	0.024	-0.004	-0.001
176	17.50	-0.039	0.111	-0.639	0.000	-0.004	-0.001
177	17.60	-0.039	0.110	-0.667	0.025	-0.004	-0.001
178	17.70	-0.040	0.109	-0.675	0.041	-0.004	-0.001
179	-	-0.041	0.107	-0.693	0.045	-0.004	-0.001
180	17.00	-0.042	0.105	-0.691	0.052	-0.004	-0.001
181	18.00	-0.043	0.103	-0.699	0.057	-0.004	-0.001
182	18.10	-0.044	0.102	-0.707	0.062	-0.004	-0.001
183	18.20	-0.044	0.097	-0.715	0.066	-0.004	-0.001
184	18.30	-0.047	0.094	-0.723	0.071	-0.004	-0.001
185	18.40	-0.040	0.090	-0.721	0.073	-0.004	-0.001
186	18.50	-0.040	0.085	-0.740	0.079	-0.004	-0.001
187	18.60	-0.050	0.081	-0.749	0.093	-0.004	-0.001
188	18.70	-0.051	0.074	-0.757	0.097	-0.004	-0.001
189	18.80	-0.052	0.070	-0.765	0.099	-0.004	-0.001
190	18.90	-0.053	0.065	-0.774	0.099	-0.004	-0.001
191	19.00	-0.055	0.058	-0.782	0.096	-0.004	-0.001
192	19.10	-0.056	0.052	-0.794	0.088	-0.004	-0.001
193	19.20	-0.059	0.043	-0.790	0.100	-0.004	-0.001
194	19.30	-0.059	0.039	-0.807	0.102	-0.004	-0.001
195	19.40	-0.059	0.031	-0.816	0.104	-0.004	-0.001
196	19.50	-0.059	0.024	-0.826	0.103	-0.004	-0.001
197	19.60	-0.062	0.015	-0.832	0.100	-0.004	-0.001
198	19.70	-0.062	0.009	-0.841	0.105	-0.004	-0.001
199	19.80	-0.065	-	-0.849	0.107	-0.004	-0.001
200	19.90	-0.066	-0.000	-0.857	0.107	-0.004	-0.001
201	20.00	-0.067	-0.017	-0.865	0.109	-0.004	-0.001
202	20.10	-0.069	-0.025	-0.873	0.106	-0.005	-0.001
203	20.20	-0.070	-0.034	-0.891	0.103	-0.005	-0.001
204	20.30	-0.070	-0.042	-0.899	0.100	-0.005	-0.001





STEP	TIME	U BODY	V BODY	W BODY	P BODY	Q BODY	P BODY
205	22.40	-0.073	-0.051	-0.806	0.102	-0.005	-0.001
206	22.50	-0.074	-0.060	-0.804	0.100	-0.005	-0.001
207	22.60	-0.076	-0.069	-0.812	0.097	-0.005	-0.001
208	22.70	-0.077	-0.077	-0.810	0.095	-0.005	-0.001
209	22.80	-0.079	-0.086	-0.827	0.092	-0.005	-0.001
210	22.90	-0.080	-0.094	-0.834	0.089	-0.005	-0.001
211	23.00	-0.082	-0.102	-0.842	0.086	-0.005	-0.000
212	23.10	-0.083	-0.110	-0.849	0.082	-0.005	-0.000
213	23.20	-0.085	-0.118	-0.857	0.078	-0.005	-0.000
214	23.30	-0.086	-0.125	-0.864	0.074	-0.005	-0.000
215	23.40	-0.088	-0.133	-0.872	0.070	-0.005	-0.000
216	23.50	-0.089	-0.139	-0.879	0.066	-0.005	-0.000
217	23.60	-0.091	-0.146	-0.887	0.061	-0.005	-0.000
218	23.70	-0.093	-0.152	-0.894	0.056	-0.005	-0.000
219	23.80	-0.095	-0.158	-0.902	0.051	-0.005	-0.000
220	23.90	-0.096	-0.164	-0.910	0.046	-0.005	-0.000
221	24.00	-0.098	-0.169	-0.917	0.041	-0.005	-0.000
222	24.10	-0.100	-0.174	-0.925	0.036	-0.005	0.000
223	24.20	-0.102	-0.178	-0.933	0.030	-0.005	0.000
224	24.30	-0.103	-0.182	-0.941	0.025	-0.005	0.000
225	24.40	-0.105	-0.185	-0.950	0.019	-0.005	0.000
226	24.50	-0.107	-0.187	-0.958	0.013	-0.005	0.000
227	24.60	-0.109	-0.190	-0.966	0.008	-0.005	0.000
228	24.70	-0.111	-0.191	-0.975	0.002	-0.005	0.000
229	24.80	-0.113	-0.192	-0.984	-0.004	-0.005	0.000
230	24.90	-0.114	-0.193	-0.993	-0.009	-0.005	0.000
231	25.00	-0.116	-0.193	-1.002	-0.015	-0.005	0.000
232	25.10	-0.119	-0.192	-1.011	-0.020	-0.005	0.000
233	25.20	-0.120	-0.191	-1.021	-0.026	-0.005	0.000
234	25.30	-0.122	-0.189	-1.030	-0.031	-0.005	0.000
235	25.40	-0.124	-0.187	-1.040	-0.036	-0.005	0.000
236	25.50	-0.127	-0.184	-1.049	-0.042	-0.005	0.000
237	25.60	-0.129	-0.180	-1.059	-0.047	-0.005	0.000
238	25.70	-0.131	-0.176	-1.069	-0.052	-0.005	0.000



STEP	TIME	U BODY	V BODY	W BODY	P BODY	Q BODY	R BODY
409	40.80	-0.709	0.433	-2.921	-0.077	0.093	-0.002
410	40.90	-0.710	0.449	-2.926	-0.068	0.093	-0.002
411	41.00	-0.712	0.464	-2.937	-0.064	0.092	-0.001
412	41.10	-0.714	0.478	-2.945	-0.063	0.092	-0.001
413	41.20	-0.716	0.492	-2.953	-0.061	0.092	-0.000
414	41.30	-0.718	0.505	-2.961	-0.059	0.093	-0.000
415	41.40	-0.720	0.517	-2.969	-0.056	0.093	0.000
416	41.50	-0.722	0.529	-2.978	-0.054	0.093	0.001
417	41.60	-0.724	0.541	-2.986	-0.051	0.093	0.001
418	41.70	-0.726	0.550	-2.994	-0.048	0.093	0.002
419	41.80	-0.727	0.560	-2.999	-0.045	0.093	0.002
420	41.90	-0.729	0.568	-3.012	-0.042	0.093	0.003
421	42.00	-0.730	0.576	-3.020	-0.040	0.092	0.003
422	42.10	-0.732	0.584	-3.029	-0.037	0.092	0.004
423	42.20	-0.735	0.590	-3.038	-0.034	0.093	0.004
424	42.30	-0.734	0.596	-3.048	-0.031	0.093	0.005
425	42.40	-0.736	0.601	-3.057	-0.029	0.093	0.005
426	42.50	-0.737	0.605	-3.067	-0.025	0.093	0.005
427	42.60	-0.738	0.608	-3.076	-0.022	0.093	0.007
428	42.70	-0.739	0.610	-3.086	-0.019	0.092	0.007
429	42.80	-0.740	0.612	-3.096	-0.016	0.093	0.008
430	42.90	-0.741	0.613	-3.107	-0.013	0.093	0.008
431	43.00	-0.742	0.613	-3.117	-0.010	0.093	0.000
432	43.10	-0.742	0.612	-3.128	-0.007	0.093	0.000
433	43.20	-0.743	0.611	-3.139	-0.004	0.092	0.000
434	43.30	-0.744	0.608	-3.150	-0.001	0.092	0.000
435	43.40	-0.745	0.605	-3.161	0.002	0.093	0.011
436	43.50	-0.745	0.601	-3.172	0.005	0.093	0.011
437	43.60	-0.746	0.596	-3.184	0.008	0.093	0.012
438	43.70	-0.746	0.590	-3.195	0.010	0.093	0.012
439	43.80	-0.747	0.584	-3.207	0.013	0.093	0.013
440	43.90	-0.747	0.577	-3.219	0.016	0.093	0.013
441	44.00	-0.748	0.569	-3.231	0.019	0.093	0.014
442	44.10	-0.748	0.560	-3.243	0.022	0.093	0.014



STP	TIME	U RDP	V RDP	W RDP	P RDP	Q RDP	R RDP
443	44.20	-0.748	0.550	-3.256	0.025	0.003	0.015
444	44.30	-0.749	0.540	-3.268	0.027	0.003	0.015
445	44.40	-0.740	0.529	-3.280	0.030	0.003	0.015
446	44.50	-0.740	0.517	-3.293	0.033	0.003	0.016
447	44.60	-0.750	0.505	-3.306	0.035	0.003	0.016
448	44.70	-0.750	0.492	-3.318	0.038	0.003	0.017
449	44.80	-0.750	0.478	-3.331	0.040	0.003	0.017
450	44.90	-0.750	0.464	-3.344	0.043	0.003	0.017
451	45.00	-0.751	0.448	-3.357	0.045	0.004	0.018
452	45.10	-0.751	0.433	-3.370	0.049	0.004	0.018
453	45.20	-0.751	0.416	-3.382	0.050	0.004	0.019
454	45.30	-0.751	0.399	-3.395	0.052	0.004	0.019
455	45.40	-0.751	0.382	-3.408	0.054	0.004	0.019
456	45.50	-0.752	0.363	-3.420	0.056	0.004	0.019
457	45.60	-0.752	0.345	-3.433	0.059	0.004	0.019
458	45.70	-0.752	0.325	-3.446	0.061	0.004	0.020
459	45.80	-0.752	0.306	-3.458	0.063	0.005	0.020
460	45.90	-0.752	0.285	-3.470	0.064	0.005	0.020
461	46.00	-0.752	0.265	-3.483	0.066	0.005	0.020
462	46.10	-0.752	0.243	-3.495	0.068	0.005	0.020
463	46.20	-0.752	0.222	-3.507	0.070	0.005	0.020
464	46.30	-0.753	0.200	-3.519	0.071	0.005	0.020
465	46.40	-0.753	0.177	-3.530	0.073	0.005	0.020
466	46.50	-0.753	0.154	-3.542	0.075	0.006	0.020
467	46.60	-0.753	0.131	-3.553	0.076	0.006	0.020
468	46.70	-0.753	0.107	-3.564	0.077	0.006	0.020
469	46.80	-0.753	0.084	-3.575	0.079	0.006	0.020
470	46.90	-0.753	0.059	-3.586	0.080	0.006	0.020
471	47.00	-0.753	0.035	-3.596	0.081	0.006	0.020
472	47.10	-0.753	0.010	-3.606	0.082	0.007	0.020
473	47.20	-0.752	-0.015	-3.616	0.084	0.007	0.020
474	47.30	-0.752	-0.040	-3.626	0.085	0.007	0.020
475	47.40	-0.752	-0.065	-3.636	0.086	0.007	0.020
476	47.50	-0.752	-0.091	-3.645	0.087	0.007	0.020



STEP TIME WEIGHT XG YG ZG SURVANCY

1	0.0	0.0	0.0	0.0	0.0	139910.4
2	0.10	139916.1	0.000	0.0	0.000	139910.4
3	0.20	139923.1	0.000	0.0	0.000	139910.4
4	0.30	139930.5	0.000	0.0	0.000	139910.4
5	0.40	139935.9	0.000	0.0	0.000	139910.4
6	0.50	139942.2	0.000	0.0	0.000	139910.4
7	0.60	139948.6	0.000	0.0	0.000	139910.4
8	0.70	139955.0	0.000	0.0	0.000	139910.4
9	0.80	139961.4	0.000	0.0	0.000	139910.4
10	0.90	139967.7	0.000	0.0	0.000	139910.4
11	1.00	139974.1	0.000	0.0	0.000	139910.4
12	1.10	139980.5	0.000	0.0	0.000	139910.4
13	1.20	139986.9	0.000	0.0	0.000	139910.4
14	1.30	139993.2	0.000	0.0	0.000	139910.4
15	1.40	139999.6	0.000	0.0	0.000	139910.4
16	1.50	139856.0	0.001	0.0	0.000	139910.4
17	1.60	139852.4	0.001	0.0	0.000	139910.4
18	1.70	139848.8	0.001	0.0	0.000	139910.4
19	1.80	139845.1	0.001	0.0	0.000	139910.4
20	1.90	139841.5	0.001	0.0	0.000	139910.4
21	2.00	139837.9	0.001	0.0	0.000	139910.4
22	2.10	139834.2	0.001	0.0	0.000	139910.4
23	2.20	139830.6	0.001	0.0	0.000	139910.4
24	2.30	139827.0	0.001	0.0	0.000	139910.4
25	2.40	139823.4	0.001	0.0	0.000	139910.4
26	2.50	139819.8	0.001	0.0	0.000	139910.4
27	2.60	139816.1	0.001	0.0	0.000	139910.4
28	2.70	139812.5	0.001	0.0	0.000	139910.4
29	2.80	139808.9	0.001	0.0	0.000	139910.4
30	2.90	139805.2	0.001	0.0	0.000	139910.4
31	3.00	139801.6	0.001	0.0	0.000	139910.4
32	3.10	139798.0	0.001	0.0	0.000	139910.4
33	3.20	139794.4	0.001	0.0	0.000	139910.4
34	3.30	139790.7	0.001	0.0	0.000	139910.4





STEP	TIME	WEIGHT	XG	YG	ZG	BUDVANCY
375	37.40	130554.6	0.023	0.0	-0.013	130910.4
376	37.50	130551.0	0.023	0.0	-0.013	130910.4
377	37.60	130547.4	0.023	0.0	-0.013	130910.4
378	37.70	130543.7	0.023	0.0	-0.013	130910.4
379	37.80	130540.1	0.023	0.0	-0.013	130910.4
380	37.90	130536.5	0.023	0.0	-0.013	130910.4
381	38.00	130532.9	0.023	0.0	-0.013	130910.4
382	38.10	130529.2	0.023	0.0	-0.014	130910.4
383	38.20	130525.6	0.023	0.0	-0.014	130910.4
384	38.30	130522.0	0.023	0.0	-0.014	130910.4
385	38.40	130518.4	0.023	0.0	-0.014	130910.4
386	38.50	130514.7	0.024	0.0	-0.014	130910.4
387	38.60	130511.1	0.024	0.0	-0.014	130910.4
388	38.70	130507.5	0.024	0.0	-0.014	130910.4
389	38.80	130503.9	0.024	0.0	-0.014	130910.4
390	38.90	130500.2	0.024	0.0	-0.014	130910.4
391	39.00	130496.6	0.024	0.0	-0.014	130910.4
392	39.10	130493.0	0.024	0.0	-0.014	130910.4
393	39.20	130489.4	0.024	0.0	-0.014	130910.4
394	39.30	130485.7	0.024	0.0	-0.014	130910.4
395	39.40	130482.1	0.024	0.0	-0.015	130910.4
396	39.50	130478.5	0.024	0.0	-0.015	130910.4
397	39.60	130474.9	0.025	0.0	-0.015	130910.4
398	39.70	130471.2	0.025	0.0	-0.015	130910.4
399	39.80	130467.6	0.025	0.0	-0.015	130910.4
400	39.90	130464.0	0.025	0.0	-0.015	130910.4
401	40.00	130460.4	0.025	0.0	-0.015	130910.4
402	40.10	130456.7	0.025	0.0	-0.015	130910.4
403	40.20	130453.1	0.025	0.0	-0.015	130910.4
404	40.30	130449.5	0.025	0.0	-0.015	130910.4
405	40.40	130445.9	0.025	0.0	-0.015	130910.4
406	40.50	130442.2	0.025	0.0	-0.015	130910.4
407	40.60	130438.6	0.025	0.0	-0.015	130910.4
408	40.70	130435.0	0.025	0.0	-0.016	130910.4



STEP TIME WEIGHT X6 V6 Z6 BUCYANCY

443	44.20	139306.1	0.020	0.0	-0.018	139910.4
444	44.30	139304.5	0.020	0.0	-0.019	139910.4
445	44.40	139303.9	0.020	0.0	-0.018	139910.4
446	44.50	139307.2	0.020	0.0	-0.010	139910.4
447	44.60	139300.6	0.020	0.0	-0.010	139910.4
448	44.70	139300.0	0.020	0.0	-0.010	139910.4
449	44.80	139306.4	0.020	0.0	-0.010	139910.4
450	44.90	139300.0	0.020	0.0	-0.010	139910.4
451	45.00	139270.1	0.020	0.0	-0.010	139910.4
452	45.10	139305.5	0.020	0.0	-0.019	139910.4
453	45.20	139301.0	0.020	0.0	-0.019	139910.4
454	45.30	139300.2	0.030	0.0	-0.019	139910.4
455	45.40	139304.6	0.030	0.0	-0.010	139910.4
456	45.50	139324.0	0.030	0.0	-0.019	139910.4
457	45.60	139257.4	0.030	0.0	-0.010	139910.4
458	45.70	139233.7	0.030	0.0	-0.010	139910.4
459	45.80	139300.1	0.030	0.0	-0.020	139910.4
460	45.90	139346.5	0.030	0.0	-0.020	139910.4
461	46.00	139242.0	0.030	0.0	-0.020	139910.4
462	46.10	139300.2	0.030	0.0	-0.020	139910.4
463	46.20	139235.6	0.030	0.0	-0.020	139910.4
464	46.30	139332.0	0.030	0.0	-0.020	139910.4
465	46.40	139220.4	0.030	0.0	-0.020	139910.4
466	46.50	139224.0	0.031	0.0	-0.020	139910.4
467	46.60	139221.1	0.031	0.0	-0.020	139910.4
468	46.70	139217.5	0.031	0.0	-0.020	139910.4
469	46.80	139213.0	0.031	0.0	-0.020	139910.4
470	46.90	139210.2	0.031	0.0	-0.020	139910.4
471	47.00	139206.6	0.031	0.0	-0.021	139910.4
472	47.10	139203.0	0.031	0.0	-0.021	139910.4
473	47.20	139199.4	0.031	0.0	-0.021	139910.4
474	47.30	139105.0	0.031	0.0	-0.021	139910.4
475	47.40	139102.1	0.031	0.0	-0.021	139910.4
476	47.50	139100.5	0.031	0.0	-0.021	139910.4







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STEP	XY	TIME	X	Y	Z	CHI	TEMP	CHI
0	1.000000	34.000000	-2.10	-1.10	-33.00	0.07	-1.20	0.10
1	1.000000	35.000000	-2.00	-2.00	-34.00	0.01	-1.30	0.10
2	1.000000	36.000000	-1.90	-4.00	-40.00	1.07	-1.20	0.10
3	1.000000	37.000000	-1.80	-4.00	-44.00	1.04	-0.26	0.10
4	1.000000	38.000000	-2.00	-3.50	-42.00	1.67	-1.00	0.10
5	1.000000	39.000000	-2.00	-3.50	-51.00	1.60	-1.00	0.10
6	1.000000	40.000000	-1.00	-4.00	-55.00	1.40	-1.00	0.10
7	1.000000	41.000000	-1.00	-3.00	-57.00	0.90	-1.00	0.10
8	1.000000	42.000000	0.00	-0.00	-60.00	0.34	-1.00	0.10
9	1.000000	43.000000	3.00	2.10	-52.00	0.10	-1.00	0.10
10	1.000000	44.000000	3.10	4.00	-52.00	0.01	-1.00	0.10
11	1.000000	45.000000	12.00	6.00	-65.00	0.07	-1.00	0.10
12	1.000000	46.000000	13.00	0.00	-57.00	1.10	-1.00	0.10
13	1.000000	47.000000	23.00	4.10	-67.00	1.00	-1.00	0.10
14	1.000000	48.000000	23.00	1.00	-47.00	0.01	-1.00	0.10
15	1.000000	49.000000	30.00	3.00	-45.00	0.04	-1.00	0.10
16	1.000000	50.000000	33.00	0.00	-30.00	0.03	-1.00	0.10
17	1.000000	51.000000	42.00	-13.00	-42.00	1.15	-1.00	0.10
18	1.000000	52.000000	47.00	-13.00	-51.00	1.30	-1.00	0.10
19	1.000000	53.000000	51.00	-12.00	-50.00	1.33	-1.00	0.10
20	1.000000	54.000000	55.00	-25.00	-53.00	1.07	-1.00	0.10
21	1.000000	55.000000	50.00	-21.00	-54.00	0.01	-1.00	0.10
22	1.000000	56.000000	60.00	-31.00	-50.00	0.10	-1.00	0.10
23	1.000000	57.000000	66.00	-34.00	-55.00	0.03	-1.00	0.10
24	1.000000	58.000000	70.00	-30.00	-55.00	0.01	-1.00	0.10
25	1.000000	59.000000	70.00	-41.00	-50.00	1.10	-1.00	0.10
26	1.000000	60.000000	76.00	-43.00	-57.00	1.00	-1.00	0.10
27	1.000000	61.000000	71.00	-45.00	-50.00	0.01	-1.00	0.10
28	1.000000	62.000000	73.00	-40.00	-60.00	0.03	-1.00	0.10
29	1.000000	63.000000	73.00	-30.00	-52.00	0.10	-1.00	0.10
30	1.000000	64.000000	73.00	-53.00	-67.00	0.01	-1.00	0.10
31	1.000000	65.000000	73.00	-40.00	-71.00	0.01	-1.00	0.10



STEP	TIME	X	Y	Z	ROLL	THETA	PSI
49	68.00	79.9	-59.0	-75.6	1.2	0.93	0.0
50	69.00	79.2	-60.7	-86.2	1.1	0.93	0.0
51	70.00	79.4	-62.5	-94.0	2.2	0.93	0.0
52	71.00	81.2	-64.6	-96.4	4.5	1.19	0.0
53	72.00	83.4	-66.9	-92.0	2.2	1.11	0.0
54	73.00	86.1	-69.2	-83.3	2.1	1.11	0.0
55	74.00	89.3	-71.2	-67.5	1.6	1.11	0.0
56	75.00	93.1	-72.7	-53.8	0.9	1.34	0.0
57	76.00	97.6	-73.7	-41.2	0.2	1.34	0.0
58	77.00	102.0	-74.2	-26.6	0.5	1.34	0.0
59	78.00	106.6	-74.1	-10.3	1.2	1.34	0.0
60	79.00	111.0	-74.1	-74.0	1.5	1.34	0.0
61	80.00	115.5	-74.1	-68.5	1.6	1.34	0.0
62	81.00	119.0	-74.6	-52.5	2.0	1.34	0.0
63	82.00	121.7	-74.9	-57.1	1.8	1.34	0.0
64	83.00	124.0	-75.1	-52.4	2.1	1.34	0.0
65	84.00	126.0	-75.6	-48.5	2.0	1.29	0.0
66	85.00	127.9	-75.6	-45.4	1.9	1.29	0.0
67	86.00	130.4	-75.8	-42.1	1.9	1.29	0.0
68	87.00	131.0	-75.1	-41.3	1.2	1.29	0.0
69	88.00	132.6	-75.0	-40.4	1.8	1.29	0.0
70	89.00	134.0	-77.1	-40.1	2.4	1.14	0.0
71	90.00	135.5	-77.6	-40.5	2.0	1.14	0.0
72	91.00	137.0	-79.2	-41.6	1.5	1.15	0.0
73	92.00	139.4	-79.0	-42.4	1.9	1.15	0.0
74	93.00	139.9	-79.4	-45.7	1.8	1.15	0.0
75	94.00	141.3	-80.1	-46.9	2.1	1.15	0.0
76	95.00	142.9	-81.6	-52.0	2.0	1.15	0.0
77	96.00	144.3	-81.5	-55.0	2.0	1.32	0.0
78	97.00	146.0	-80.6	-60.0	1.4	1.32	0.0
79	98.00	149.9	-80.1	-56.0	2.0	1.32	0.0
80	99.00	151.0	-79.5	-50.5	2.0	1.32	0.0
81	100.00	153.1	-79.0	-49.4	2.1	1.32	0.0
82	101.00	155.0	-79.0	-49.0	1.8	1.32	0.0













S	T	W	P	R	K
300V	300V	300V	300V	300V	300V
34.0	-0.750	-0.056	0.577	-0.024	0.04
35.0	-0.076	-1.777	0.521	0.002	0.00
36.0	-1.205	-2.113	0.437	0.000	0.04
37.0	-1.450	-3.650	0.313	-0.000	-0.01
38.0	-1.000	-3.740	0.121	-0.000	-0.00
39.0	-0.000	-3.203	-0.140	-0.000	-0.00
40.0	-0.000	-3.040	-0.423	-0.000	-0.00
41.0	-0.000	-2.523	-0.040	-0.000	-0.00
42.0	-0.523	-0.700	-0.703	-0.000	-0.00
43.0	-0.000	0.150	-0.033	-0.000	-0.00
44.0	-0.000	4.000	-0.552	-0.000	-0.00
45.0	-0.000	4.000	-0.370	-0.000	-0.00
46.0	-0.000	3.000	-0.027	-0.000	-0.00
47.0	-0.000	3.000	0.315	-0.000	-0.00
48.0	-0.000	3.000	0.504	-0.000	-0.00
49.0	-0.000	1.270	0.000	-0.000	-0.00
50.0	-0.000	1.000	0.000	-0.000	-0.00
51.0	-0.000	1.000	0.000	-0.000	-0.00
52.0	-0.000	1.000	0.000	-0.000	-0.00
53.0	-0.000	1.000	0.000	-0.000	-0.00
54.0	-0.000	1.000	0.000	-0.000	-0.00
55.0	-0.000	1.000	0.000	-0.000	-0.00
56.0	-0.000	1.000	0.000	-0.000	-0.00
57.0	-0.000	1.000	0.000	-0.000	-0.00
58.0	-0.000	1.000	0.000	-0.000	-0.00
59.0	-0.000	1.000	0.000	-0.000	-0.00
60.0	-0.000	1.000	0.000	-0.000	-0.00
61.0	-0.000	1.000	0.000	-0.000	-0.00
62.0	-0.000	1.000	0.000	-0.000	-0.00
63.0	-0.000	1.000	0.000	-0.000	-0.00
64.0	-0.000	1.000	0.000	-0.000	-0.00
65.0	-0.000	1.000	0.000	-0.000	-0.00
66.0	-0.000	1.000	0.000	-0.000	-0.00
67.0	-0.000	1.000	0.000	-0.000	-0.00
68.0	-0.000	1.000	0.000	-0.000	-0.00
69.0	-0.000	1.000	0.000	-0.000	-0.00
70.0	-0.000	1.000	0.000	-0.000	-0.00
71.0	-0.000	1.000	0.000	-0.000	-0.00
72.0	-0.000	1.000	0.000	-0.000	-0.00
73.0	-0.000	1.000	0.000	-0.000	-0.00
74.0	-0.000	1.000	0.000	-0.000	-0.00
75.0	-0.000	1.000	0.000	-0.000	-0.00
76.0	-0.000	1.000	0.000	-0.000	-0.00
77.0	-0.000	1.000	0.000	-0.000	-0.00
78.0	-0.000	1.000	0.000	-0.000	-0.00
79.0	-0.000	1.000	0.000	-0.000	-0.00
80.0	-0.000	1.000	0.000	-0.000	-0.00
81.0	-0.000	1.000	0.000	-0.000	-0.00
82.0	-0.000	1.000	0.000	-0.000	-0.00
83.0	-0.000	1.000	0.000	-0.000	-0.00
84.0	-0.000	1.000	0.000	-0.000	-0.00
85.0	-0.000	1.000	0.000	-0.000	-0.00
86.0	-0.000	1.000	0.000	-0.000	-0.00
87.0	-0.000	1.000	0.000	-0.000	-0.00
88.0	-0.000	1.000	0.000	-0.000	-0.00
89.0	-0.000	1.000	0.000	-0.000	-0.00
90.0	-0.000	1.000	0.000	-0.000	-0.00
91.0	-0.000	1.000	0.000	-0.000	-0.00
92.0	-0.000	1.000	0.000	-0.000	-0.00
93.0	-0.000	1.000	0.000	-0.000	-0.00
94.0	-0.000	1.000	0.000	-0.000	-0.00
95.0	-0.000	1.000	0.000	-0.000	-0.00
96.0	-0.000	1.000	0.000	-0.000	-0.00
97.0	-0.000	1.000	0.000	-0.000	-0.00
98.0	-0.000	1.000	0.000	-0.000	-0.00
99.0	-0.000	1.000	0.000	-0.000	-0.00
100.0	-0.000	1.000	0.000	-0.000	-0.00











STEP	TIME	U DOT	V DOT	W DOT	X DOT	Y DOT	Z DOT
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.001	-0.001	-0.004	0.000	-0.000	-0.000	0.000
3	0.001	-0.001	-0.004	0.000	-0.000	-0.000	0.000
4	0.002	-0.002	-0.008	0.000	-0.000	-0.000	0.000
5	0.003	-0.003	-0.012	0.000	-0.000	-0.000	0.000
6	0.004	-0.004	-0.016	0.000	-0.000	-0.000	0.000
7	0.005	-0.005	-0.020	0.000	-0.000	-0.000	0.000
8	0.006	-0.006	-0.024	0.000	-0.000	-0.000	0.000
9	0.007	-0.007	-0.028	0.000	-0.000	-0.000	0.000
10	0.008	-0.008	-0.032	0.000	-0.000	-0.000	0.000
11	0.009	-0.009	-0.036	0.000	-0.000	-0.000	0.000
12	0.010	-0.010	-0.040	0.000	-0.000	-0.000	0.000
13	0.011	-0.011	-0.044	0.000	-0.000	-0.000	0.000
14	0.012	-0.012	-0.048	0.000	-0.000	-0.000	0.000
15	0.013	-0.013	-0.052	0.000	-0.000	-0.000	0.000
16	0.014	-0.014	-0.056	0.000	-0.000	-0.000	0.000
17	0.015	-0.015	-0.060	0.000	-0.000	-0.000	0.000
18	0.016	-0.016	-0.064	0.000	-0.000	-0.000	0.000
19	0.017	-0.017	-0.068	0.000	-0.000	-0.000	0.000
20	0.018	-0.018	-0.072	0.000	-0.000	-0.000	0.000
21	0.019	-0.019	-0.076	0.000	-0.000	-0.000	0.000
22	0.020	-0.020	-0.080	0.000	-0.000	-0.000	0.000
23	0.021	-0.021	-0.084	0.000	-0.000	-0.000	0.000
24	0.022	-0.022	-0.088	0.000	-0.000	-0.000	0.000
25	0.023	-0.023	-0.092	0.000	-0.000	-0.000	0.000
26	0.024	-0.024	-0.096	0.000	-0.000	-0.000	0.000
27	0.025	-0.025	-0.100	0.000	-0.000	-0.000	0.000
28	0.026	-0.026	-0.104	0.000	-0.000	-0.000	0.000
29	0.027	-0.027	-0.108	0.000	-0.000	-0.000	0.000
30	0.028	-0.028	-0.112	0.000	-0.000	-0.000	0.000
31	0.029	-0.029	-0.116	0.000	-0.000	-0.000	0.000
32	0.030	-0.030	-0.120	0.000	-0.000	-0.000	0.000
33	0.031	-0.031	-0.124	0.000	-0.000	-0.000	0.000
34	0.032	-0.032	-0.128	0.000	-0.000	-0.000	0.000
35	0.033	-0.033	-0.132	0.000	-0.000	-0.000	0.000
36	0.034	-0.034	-0.136	0.000	-0.000	-0.000	0.000
37	0.035	-0.035	-0.140	0.000	-0.000	-0.000	0.000
38	0.036	-0.036	-0.144	0.000	-0.000	-0.000	0.000
39	0.037	-0.037	-0.148	0.000	-0.000	-0.000	0.000
40	0.038	-0.038	-0.152	0.000	-0.000	-0.000	0.000
41	0.039	-0.039	-0.156	0.000	-0.000	-0.000	0.000
42	0.040	-0.040	-0.160	0.000	-0.000	-0.000	0.000
43	0.041	-0.041	-0.164	0.000	-0.000	-0.000	0.000
44	0.042	-0.042	-0.168	0.000	-0.000	-0.000	0.000
45	0.043	-0.043	-0.172	0.000	-0.000	-0.000	0.000
46	0.044	-0.044	-0.176	0.000	-0.000	-0.000	0.000
47	0.045	-0.045	-0.180	0.000	-0.000	-0.000	0.000
48	0.046	-0.046	-0.184	0.000	-0.000	-0.000	0.000
49	0.047	-0.047	-0.188	0.000	-0.000	-0.000	0.000
50	0.048	-0.048	-0.192	0.000	-0.000	-0.000	0.000
51	0.049	-0.049	-0.196	0.000	-0.000	-0.000	0.000
52	0.050	-0.050	-0.200	0.000	-0.000	-0.000	0.000
53	0.051	-0.051	-0.204	0.000	-0.000	-0.000	0.000
54	0.052	-0.052	-0.208	0.000	-0.000	-0.000	0.000
55	0.053	-0.053	-0.212	0.000	-0.000	-0.000	0.000
56	0.054	-0.054	-0.216	0.000	-0.000	-0.000	0.000
57	0.055	-0.055	-0.220	0.000	-0.000	-0.000	0.000
58	0.056	-0.056	-0.224	0.000	-0.000	-0.000	0.000
59	0.057	-0.057	-0.228	0.000	-0.000	-0.000	0.000
60	0.058	-0.058	-0.232	0.000	-0.000	-0.000	0.000
61	0.059	-0.059	-0.236	0.000	-0.000	-0.000	0.000
62	0.060	-0.060	-0.240	0.000	-0.000	-0.000	0.000
63	0.061	-0.061	-0.244	0.000	-0.000	-0.000	0.000
64	0.062	-0.062	-0.248	0.000	-0.000	-0.000	0.000
65	0.063	-0.063	-0.252	0.000	-0.000	-0.000	0.000
66	0.064	-0.064	-0.256	0.000	-0.000	-0.000	0.000
67	0.065	-0.065	-0.260	0.000	-0.000	-0.000	0.000
68	0.066	-0.066	-0.264	0.000	-0.000	-0.000	0.000
69	0.067	-0.067	-0.268	0.000	-0.000	-0.000	0.000
70	0.068	-0.068	-0.272	0.000	-0.000	-0.000	0.000
71	0.069	-0.069	-0.276	0.000	-0.000	-0.000	0.000
72	0.070	-0.070	-0.280	0.000	-0.000	-0.000	0.000
73	0.071	-0.071	-0.284	0.000	-0.000	-0.000	0.000
74	0.072	-0.072	-0.288	0.000	-0.000	-0.000	0.000
75	0.073	-0.073	-0.292	0.000	-0.000	-0.000	0.000
76	0.074	-0.074	-0.296	0.000	-0.000	-0.000	0.000
77	0.075	-0.075	-0.300	0.000	-0.000	-0.000	0.000
78	0.076	-0.076	-0.304	0.000	-0.000	-0.000	0.000
79	0.077	-0.077	-0.308	0.000	-0.000	-0.000	0.000
80	0.078	-0.078	-0.312	0.000	-0.000	-0.000	0.000
81	0.079	-0.079	-0.316	0.000	-0.000	-0.000	0.000
82	0.080	-0.080	-0.320	0.000	-0.000	-0.000	0.000
83	0.081	-0.081	-0.324	0.000	-0.000	-0.000	0.000
84	0.082	-0.082	-0.328	0.000	-0.000	-0.000	0.000
85	0.083	-0.083	-0.332	0.000	-0.000	-0.000	0.000
86	0.084	-0.084	-0.336	0.000	-0.000	-0.000	0.000
87	0.085	-0.085	-0.340	0.000	-0.000	-0.000	0.000
88	0.086	-0.086	-0.344	0.000	-0.000	-0.000	0.000
89	0.087	-0.087	-0.348	0.000	-0.000	-0.000	0.000
90	0.088	-0.088	-0.352	0.000	-0.000	-0.000	0.000
91	0.089	-0.089	-0.356	0.000	-0.000	-0.000	0.000
92	0.090	-0.090	-0.360	0.000	-0.000	-0.000	0.000
93	0.091	-0.091	-0.364	0.000	-0.000	-0.000	0.000
94	0.092	-0.092	-0.368	0.000	-0.000	-0.000	0.000
95	0.093	-0.093	-0.372	0.000	-0.000	-0.000	0.000
96	0.094	-0.094	-0.376	0.000	-0.000	-0.000	0.000
97	0.095	-0.095	-0.380	0.000	-0.000	-0.000	0.000
98	0.096	-0.096	-0.384	0.000	-0.000	-0.000	0.000
99	0.097	-0.097	-0.388	0.000	-0.000	-0.000	0.000
100	0.098	-0.098	-0.392	0.000	-0.000	-0.000	0.000









TIME	TEMP	VOLT	AMP	WATT	REMARKS
69.00	1.496	-0.673	1.505	0.025	
69.05	-0.153	-0.369	1.520	-0.019	
70.00	0.312	-0.238	1.750	-0.019	
70.05	0.399	0.312	1.200	0.021	
70.10	0.192	0.526	0.300	0.026	
70.15	1.279	-0.140	-0.544	-0.017	
70.20	1.255	-0.747	-1.365	-0.121	
70.25	1.499	-0.197	-2.174	-0.100	
70.30	1.379	1.213	-2.448	0.058	
70.35	1.123	2.507	-1.009	0.022	
70.40	0.975	2.044	1.150	0.011	
70.45	0.516	0.432	1.644	0.016	
70.50	0.140	-0.347	0.842	-0.013	
70.55	-0.692	-0.524	0.131	0.022	
71.00	-0.049	-0.330	-0.112	0.007	
71.05	-0.170	-0.336	-0.174	0.071	
71.10	-0.115	-0.311	-0.200	0.053	
71.15	-0.390	-0.223	-0.209	0.060	
71.20	-0.731	-0.266	-0.192	0.045	
71.25	-0.725	-0.011	-0.160	0.041	
71.30	-1.504	-0.373	-0.100	0.020	
71.35	-0.600	-0.450	-0.010	0.021	
71.40	-0.631	-0.491	0.120	0.051	
71.45	-0.501	-0.470	0.300	0.021	
71.50	-0.547	-0.603	0.500	0.000	
71.55	-0.400	-0.333	0.700	0.042	
72.00	-0.420	0.155	0.400	0.011	
72.05	-0.714	0.395	0.700	0.030	
72.10	-0.291	0.367	0.500	0.030	
72.15	-0.330	0.347	0.360	0.030	
72.20	-0.245	0.041	0.200	0.000	
72.25	-0.220	0.011	0.007	0.000	
72.30	-0.290	-0.512	0.000	0.000	
72.35	-0.110	-0.000	0.000	0.000	







## APPENDIX D

### A PROGRAM TO COMPUTE THE ONE DIMENSIONAL ACCELERATION TRAJECTORY

In order to complete the one dimensional acceleration trajectory developed in Chapter III, the program listed on the following page was written.

This program reads in initial conditions and deballasting parameters, computes the acceleration velocity and distance traveled by the vehicle.









Summary of Results

Input Data

\$1000000 = 1000000.0,  $\alpha = 0.0$ ,  $\beta = 0.0$ ,  $\gamma = 0.0$ ,  $\delta = 0.0$ ,  $\epsilon = 0.0$ ,

$D = 35.227286$ ,  $A = 3767.80$ ,  $L = 205.5$ ,  $W = 0.50$ ,  $H = 88$ ,  $T = 300$ ,

$J = 1$ , \$0.00



STEP	WEIGHT	BURDANCY	DOT	W	Z	FACTOR
1	140000.00	35.23	-0.004	-0.002	-0.00	-0.35
2	140000.00	70.47	-0.009	-0.007	-0.00	-0.60
3	140000.00	105.72	-0.013	-0.012	-0.01	-0.71
4	140000.00	140.93	-0.017	-0.022	-0.02	-0.82
5	140000.00	176.16	-0.022	-0.023	-0.03	-0.93
6	140000.00	211.40	-0.026	-0.046	-0.05	-0.95
7	140000.00	246.63	-0.030	-0.061	-0.08	-0.98
8	140000.00	281.86	-0.035	-0.078	-0.11	-0.99
9	140000.00	317.10	-0.039	-0.098	-0.15	-0.99
10	140000.00	352.33	-0.043	-0.119	-0.21	-0.99
11	140000.00	387.56	-0.047	-0.143	-0.27	-0.99
12	140000.00	422.80	-0.052	-0.169	-0.35	-0.99
13	140000.00	458.03	-0.056	-0.197	-0.44	-0.99
14	140000.00	493.26	-0.060	-0.227	-0.55	-0.99
15	140000.00	528.49	-0.064	-0.258	-0.67	-0.99
16	140000.00	563.73	-0.068	-0.292	-0.81	-0.99
17	140000.00	598.96	-0.072	-0.328	-0.96	-0.99
18	140000.00	634.19	-0.076	-0.366	-1.14	-0.99
19	140000.00	669.43	-0.079	-0.406	-1.32	-0.99
20	140000.00	704.66	-0.083	-0.447	-1.54	-0.99
21	140000.00	739.89	-0.086	-0.490	-1.78	-0.99
22	140000.00	775.12	-0.090	-0.535	-2.03	-0.99
23	140000.00	810.36	-0.093	-0.582	-2.31	-0.99
24	140000.00	845.59	-0.096	-0.629	-2.62	-0.99
25	140000.00	880.82	-0.099	-0.679	-2.94	-0.99
26	140000.00	916.06	-0.102	-0.730	-3.30	-0.99
27	140000.00	951.29	-0.104	-0.782	-3.67	-0.99
28	140000.00	986.52	-0.106	-0.835	-4.08	-0.99
29	140000.00	1021.75	-0.109	-0.889	-4.51	-0.99
30	140000.00	1056.99	-0.111	-0.944	-4.97	-0.99
31	140000.00	1092.22	-0.112	-1.001	-5.45	-0.99
32	140000.00	1127.45	-0.114	-1.058	-5.97	-0.99
33	140000.00	1162.69	-0.115	-1.115	-6.51	-0.99
34	140000.00	1197.92	-0.117	-1.174	-7.08	-0.99
35	140000.00	1233.15	-0.118	-1.232	-7.68	-0.99
36	140000.00	1268.39	-0.119	-1.292	-8.32	-0.99
37	140000.00	1303.62	-0.119	-1.351	-8.98	-0.99
38	140000.00	1338.85	-0.119	-1.411	-9.67	-0.99
39	140000.00	1374.08	-0.119	-1.470	-10.39	-0.99
40	140000.00	1409.32	-0.119	-1.530	-11.14	-0.99
41	140000.00	1444.55	-0.119	-1.590	-11.92	-0.99
42	140000.00	1479.78	-0.119	-1.649	-12.73	-0.99
43	140000.00	1515.02	-0.118	-1.708	-13.57	-0.99
44	140000.00	1550.25	-0.118	-1.767	-14.43	-0.99
45	140000.00	1585.48	-0.117	-1.825	-15.33	-0.99
46	140000.00	1620.71	-0.116	-1.883	-16.26	-0.99
47	140000.00	1655.95	-0.115	-1.941	-17.22	-0.99
48	140000.00	1691.18	-0.114	-1.998	-18.20	-0.99
49	140000.00	1726.41	-0.112	-2.056	-19.21	-0.99
50	140000.00	1761.65	-0.111	-2.114	-20.25	-0.99



STEP	HEIGHT	+ BUOYANCY	DOT	W	Z	FACTOR
51	140000.00	1796.88	-0.109	-2.114		-21.34
52	140000.00	1832.11	-0.108	-2.218		-22.42
53	140000.00	1867.34	-0.106	-2.271		-23.54
54	140000.00	1902.58	-0.104	-2.323		-24.62
55	140000.00	1937.81	-0.103	-2.374		-25.36
56	140000.00	1973.04	-0.101	-2.425		-27.06
57	140000.00	2008.28	-0.099	-2.474		-28.29
58	140000.00	2043.51	-0.097	-2.523		-29.54
59	140000.00	2078.74	-0.095	-2.571		-30.81
60	140000.00	2113.98	-0.094	-2.617		-32.11
61	140000.00	2149.21	-0.092	-2.663		-33.43
62	140000.00	2184.44	-0.090	-2.708		-34.77
63	140000.00	2219.67	-0.088	-2.752		-36.13
64	140000.00	2254.91	-0.086	-2.796		-37.52
65	140000.00	2290.14	-0.085	-2.838		-38.93
66	140000.00	2325.37	-0.083	-2.879		-40.36
67	140000.00	2360.61	-0.081	-2.920		-41.81
68	140000.00	2395.84	-0.080	-2.960		-43.28
69	140000.00	2431.07	-0.078	-2.999		-44.77
70	140000.00	2466.30	-0.077	-3.037		-46.28
71	140000.00	2501.54	-0.075	-3.075		-47.81
72	140000.00	2536.77	-0.074	-3.112		-49.35
73	140000.00	2572.00	-0.072	-3.148		-50.92
74	140000.00	2607.24	-0.071	-3.183		-52.50
75	140000.00	2642.47	-0.069	-3.218		-54.10
76	140000.00	2677.70	-0.068	-3.252		-55.72
77	140000.00	2712.93	-0.067	-3.285		-57.35
78	140000.00	2748.17	-0.066	-3.318		-59.00
79	140000.00	2783.40	-0.064	-3.350		-60.57
80	140000.00	2818.63	-0.063	-3.382		-62.35
81	140000.00	2853.87	-0.062	-3.413		-64.05
82	140000.00	2889.10	-0.061	-3.444		-65.76
83	140000.00	2924.33	-0.060	-3.474		-67.49
84	140000.00	2959.56	-0.059	-3.503		-69.24
85	140000.00	2994.80	-0.058	-3.533		-71.00
86	140000.00	3030.03	-0.058	-3.561		-72.77
87	140000.00	3065.26	-0.057	-3.590		-74.56
88	140000.00	3100.50	-0.056	-3.618		-76.36
89	140000.00	3100.50	-0.051	-3.643		-78.18
90	140000.00	3100.50	-0.046	-3.666		-80.00
91	140000.00	3100.50	-0.042	-3.687		-81.84
92	140000.00	3100.50	-0.038	-3.706		-83.69
93	140000.00	3100.50	-0.034	-3.723		-85.55
94	140000.00	3100.50	-0.031	-3.738		-87.41
95	140000.00	3100.50	-0.028	-3.752		-89.26
96	140000.00	3100.50	-0.025	-3.765		-91.16
97	140000.00	3100.50	-0.023	-3.776		-93.05
98	140000.00	3100.50	-0.021	-3.787		-94.94
99	140000.00	3100.50	-0.019	-3.796		-96.84
100	140000.00	3100.50	-0.017	-3.804		-98.74
101	140000.00	3100.50	-0.015	-3.812		-100.64





STEP	WEIGHT	+ BUOYANCY	W DOT	W	Z FAP1H
102	140000.00	3100.50	-0.014	-3.819	-102.55
103	140000.00	3100.50	-0.012	-3.825	-104.46
104	140000.00	3100.50	-0.011	-3.831	-106.37
105	140000.00	3100.50	-0.010	-3.836	-108.29
106	140000.00	3100.50	-0.009	-3.840	-110.21
107	140000.00	3100.50	-0.008	-3.844	-112.13
108	140000.00	3100.50	-0.007	-3.848	-114.05
109	140000.00	3100.50	-0.007	-3.851	-115.98
110	140000.00	3100.50	-0.006	-3.854	-117.90
111	140000.00	3100.50	-0.005	-3.857	-119.83
112	140000.00	3100.50	-0.005	-3.859	-121.76
113	140000.00	3100.50	-0.004	-3.862	-123.69
114	140000.00	3100.50	-0.004	-3.864	-125.62
115	140000.00	3100.50	-0.004	-3.865	-127.55
116	140000.00	3100.50	-0.003	-3.867	-129.49
117	140000.00	3100.50	-0.003	-3.868	-131.42
118	140000.00	3100.50	-0.003	-3.870	-133.35
119	140000.00	3100.50	-0.002	-3.871	-135.29
120	140000.00	3100.50	-0.002	-3.872	-137.23
121	140000.00	3100.50	-0.002	-3.873	-139.16
122	140000.00	3100.50	-0.002	-3.874	-141.10
123	140000.00	3100.50	-0.002	-3.874	-143.04
124	140000.00	3100.50	-0.001	-3.875	-144.97
125	140000.00	3100.50	-0.001	-3.876	-146.91
126	140000.00	3100.50	-0.001	-3.876	-148.85
127	140000.00	3100.50	-0.001	-3.877	-150.79
128	140000.00	3100.50	-0.001	-3.877	-152.73
129	140000.00	3100.50	-0.001	-3.878	-154.66
130	140000.00	3100.50	-0.001	-3.878	-156.60
131	140000.00	3100.50	-0.001	-3.878	-158.54
132	140000.00	3100.50	-0.001	-3.879	-160.48
133	140000.00	3100.50	-0.001	-3.879	-162.42
134	140000.00	3100.50	-0.000	-3.879	-164.36
135	140000.00	3100.50	-0.000	-3.879	-166.30
136	140000.00	3100.50	-0.000	-3.880	-168.24
137	140000.00	3100.50	-0.000	-3.880	-170.18
138	140000.00	3100.50	-0.000	-3.880	-172.12
139	140000.00	3100.50	-0.000	-3.880	-174.06
140	140000.00	3100.50	-0.000	-3.880	-176.00
141	140000.00	3100.50	-0.000	-3.880	-177.94
142	140000.00	3100.50	-0.000	-3.880	-179.88
143	140000.00	3100.50	-0.000	-3.881	-181.82
144	140000.00	3100.50	-0.000	-3.881	-183.76
145	140000.00	3100.50	-0.000	-3.881	-185.70
146	140000.00	3100.50	-0.000	-3.881	-187.64
147	140000.00	3100.50	-0.000	-3.881	-189.58
148	140000.00	3100.50	-0.000	-3.881	-191.52
149	140000.00	3100.50	-0.000	-3.881	-193.46
150	140000.00	3100.50	-0.000	-3.881	-195.40
151	140000.00	3100.50	-0.000	-3.881	-197.34
152	140000.00	3100.50	-0.000	-3.881	-199.28



STEP	HEIGHT	+ BUOYANCY	DEPTH	W	Z EARTH
153	140000.00	3100.50	-0.000	-3.881	-201.22
154	140000.00	3100.50	-0.000	-3.881	-203.17
155	140000.00	3100.50	-0.000	-3.881	-205.11
156	140000.00	3100.50	-0.000	-3.881	-207.05
157	140000.00	3100.50	-0.000	-3.881	-208.99
158	140000.00	3100.50	-0.000	-3.881	-210.93
159	140000.00	3100.50	-0.000	-3.881	-212.87
160	140000.00	3100.50	-0.000	-3.881	-214.81
161	140000.00	3100.50	-0.000	-3.881	-216.75
162	140000.00	3100.50	-0.000	-3.881	-218.69
163	140000.00	3100.50	-0.000	-3.881	-220.63
164	140000.00	3100.50	-0.000	-3.881	-222.57
165	140000.00	3100.50	-0.000	-3.881	-224.51
166	140000.00	3100.50	-0.000	-3.881	-226.45
167	140000.00	3100.50	-0.000	-3.881	-228.39
168	140000.00	3100.50	-0.000	-3.881	-230.33
169	140000.00	3100.50	-0.000	-3.881	-232.28
170	140000.00	3100.50	-0.000	-3.881	-234.22
171	140000.00	3100.50	-0.000	-3.881	-236.16
172	140000.00	3100.50	-0.000	-3.881	-238.10
173	140000.00	3100.50	-0.000	-3.881	-240.04
174	140000.00	3100.50	-0.000	-3.881	-241.98
175	140000.00	3100.50	-0.000	-3.881	-243.92
176	140000.00	3100.50	-0.000	-3.881	-245.86
177	140000.00	3100.50	-0.000	-3.881	-247.80
178	140000.00	3100.50	-0.000	-3.881	-249.74
179	140000.00	3100.50	-0.000	-3.881	-251.68
180	140000.00	3100.50	-0.000	-3.881	-253.62
181	140000.00	3100.50	-0.000	-3.881	-255.56
182	140000.00	3100.50	-0.000	-3.881	-257.50
183	140000.00	3100.50	-0.000	-3.881	-259.44
184	140000.00	3100.50	-0.000	-3.881	-261.39
185	140000.00	3100.50	-0.000	-3.881	-263.33
186	140000.00	3100.50	-0.000	-3.881	-265.27
187	140000.00	3100.50	-0.000	-3.881	-267.21
188	140000.00	3100.50	-0.000	-3.881	-269.15
189	140000.00	3100.50	-0.000	-3.881	-271.09
190	140000.00	3100.50	-0.000	-3.881	-273.03
191	140000.00	3100.50	-0.000	-3.881	-274.97
192	140000.00	3100.50	-0.000	-3.881	-276.91
193	140000.00	3100.50	-0.000	-3.881	-278.85
194	140000.00	3100.50	-0.000	-3.881	-280.79
195	140000.00	3100.50	-0.000	-3.881	-282.73
196	140000.00	3100.50	-0.000	-3.881	-284.67
197	140000.00	3100.50	-0.000	-3.881	-286.61
198	140000.00	3100.50	-0.000	-3.881	-288.55
199	140000.00	3100.50	-0.000	-3.881	-290.50
200	140000.00	3100.50	-0.000	-3.881	-292.44
201	140000.00	3100.50	-0.000	-3.881	-294.38
202	140000.00	3100.50	-0.000	-3.881	-296.32
203	140000.00	3100.50	-0.000	-3.881	-298.26







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Emergency ascent trajectories for deep s



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